Exploring Protoplanetary Disk Evolution with the Spitzer Space Telescope

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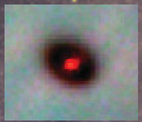
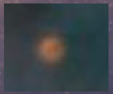
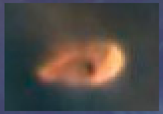
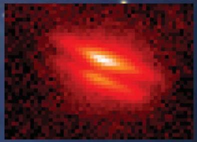
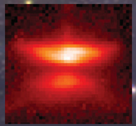




in collaboration with members of the IRS_Disks team:

D. M. Watson, W. J. Forrest, Manoj P., K. H. Kim (Rochester),
M. K. McClure, N. Calvet, L. Hartmann (Michigan), C. Espaillat (CfA),
P. D'Alessio (UNAM), K. Luhman (Penn State), B. Sargent (STScI)

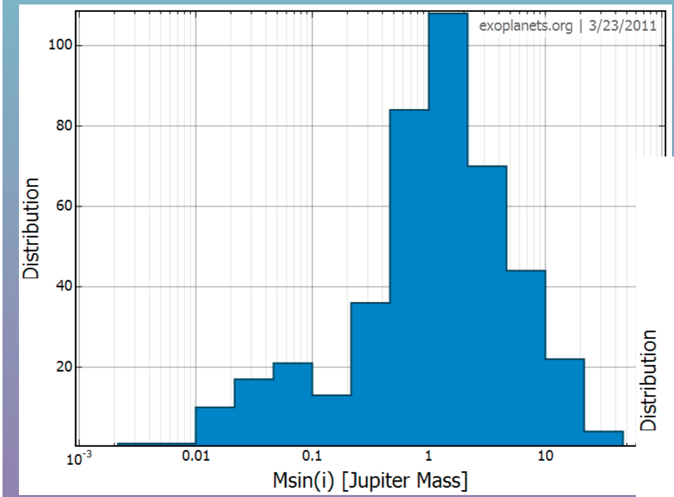
Background credit: NASA/JPL-Caltech

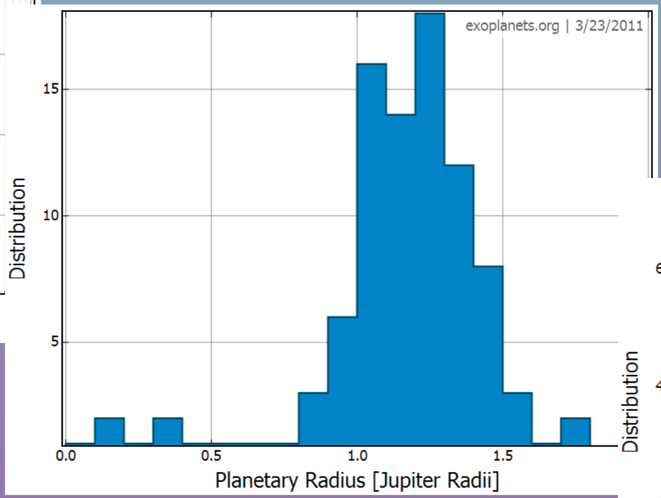
Motivation

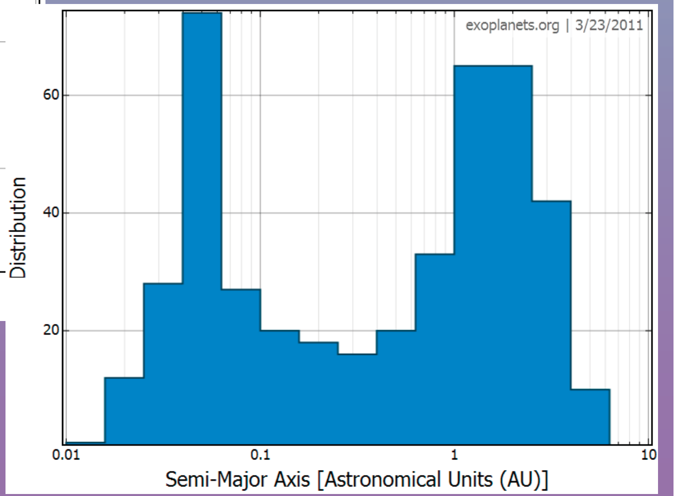
Where do we come from? Are we alone?

★ first planets around a solar-type star detected in 1995

★ now: over 400 planetary systems known (with > 1000 candidates), most are less than 1 Jupiter mass, but about the size of Jupiter, and orbit within 1 AU from their star; dozens of multiple systems







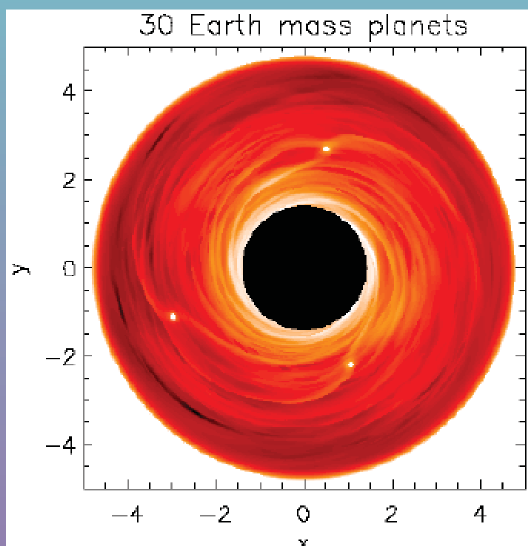
Motivation

★ planets form in protoplanetary disks → search for evidence

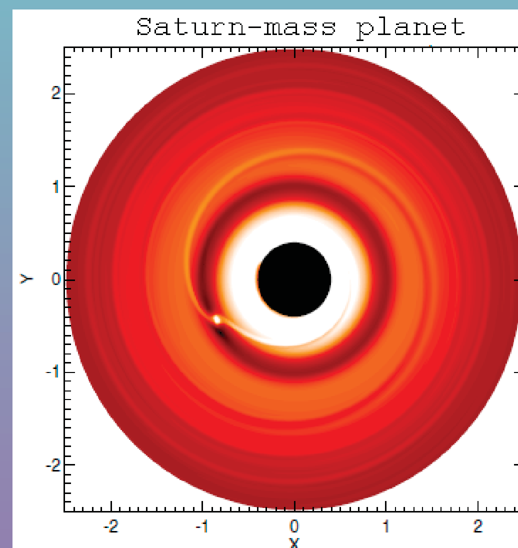
- dust grain growth, settling
- inner disk holes
- disk gaps

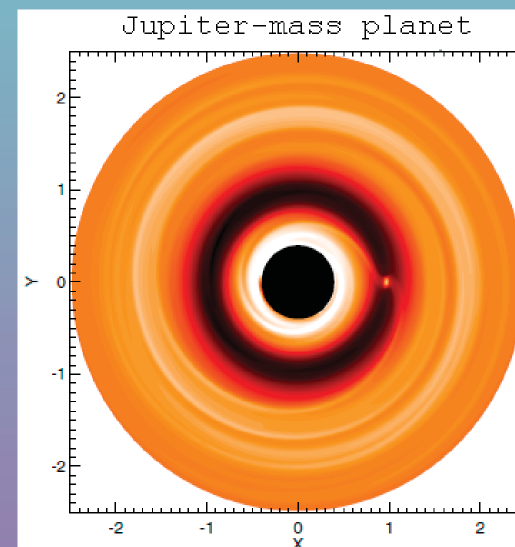
(• image planets in disks)

decreased emission from dust in the inner disk



(Nelson 2005)





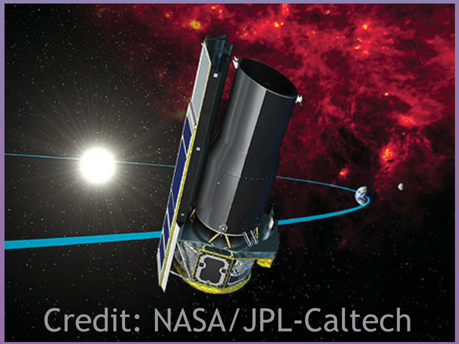
(Pierens & Nelson 2010)

★ study young (1-3 Myr-old) disks to observe first stages of planet formation

→ constrain mechanisms and timescales of planet formation, processes leading to disk dissipation

The Spitzer Space Telescope

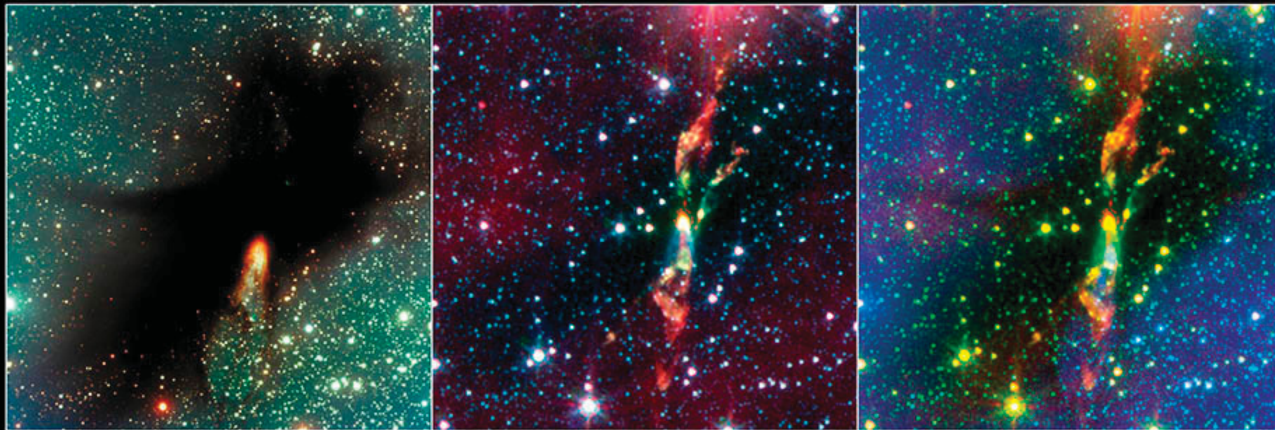
- 85 cm telescope
- three scientific instruments:
  - **Infrared Array Camera (IRAC):** imaging at 3.6, 4.5, 5.8 and 8 μm
  - **Multiband Imaging Photometer (MIPS):** imaging at 24, 70, 160 μm
  - **Infrared Spectrograph (IRS):** low-resolution spectra: 5-38 μm; medium-resolution spectra: 10-37 μm
- launched in August 2003
- cryogen depleted on May 15, 2009
  → only IRAC band 1 and 2 operational today
- heliocentric (Earth-trailing) orbit



Credit: NASA/JPL-Caltech

Credit: Russ Underwood, Lockheed Martin Space Systems


August 25, 2003
1:35 AM EDT
Kennedy Space Center
Cape Canaveral, Florida

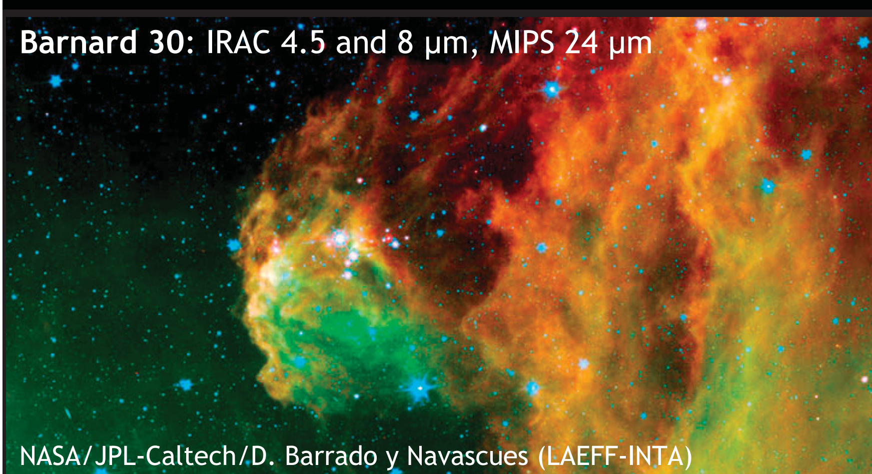


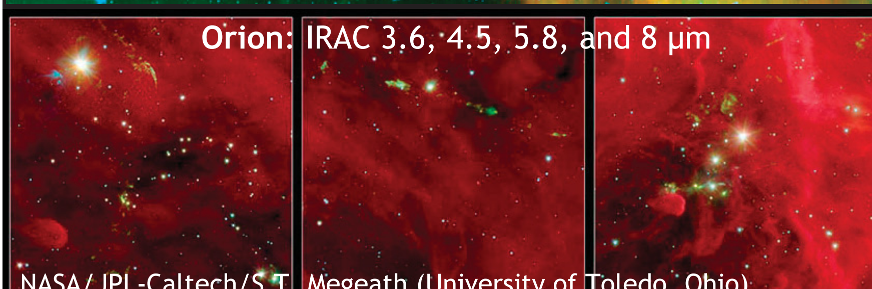
Visible (VLT) Infrared Combined

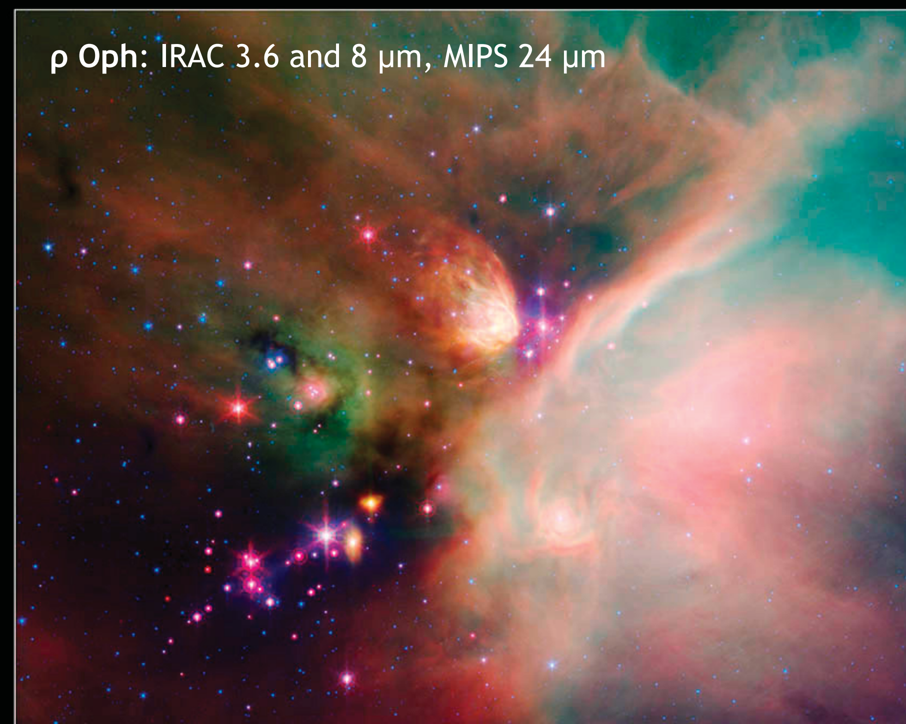
IRAC 3.6 μm, 4.5 μm, 8 μm

Protostellar Jet in BHR 71 Dark Cloud **Spitzer Space Telescope • IRAC**

NASA / JPL-Caltech / T. Bourke (Harvard-Smithsonian CfA)







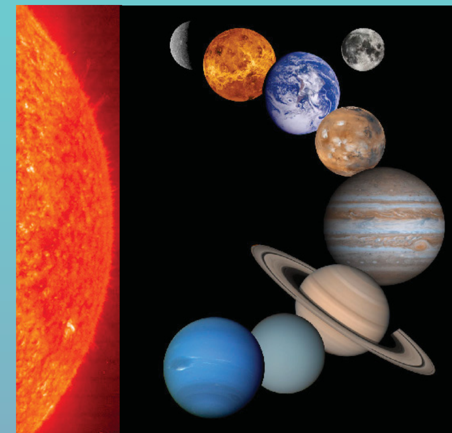
Star Formation in the Rho Ophiuchi Cloud **Spitzer Space Telescope • IRAC • MIPS**

NASA / JPL-Caltech / L. Allen (Harvard-Smithsonian CfA) & D. Padgett (SSC-Caltech) ssc2008-03a

Low-Mass Star Formation

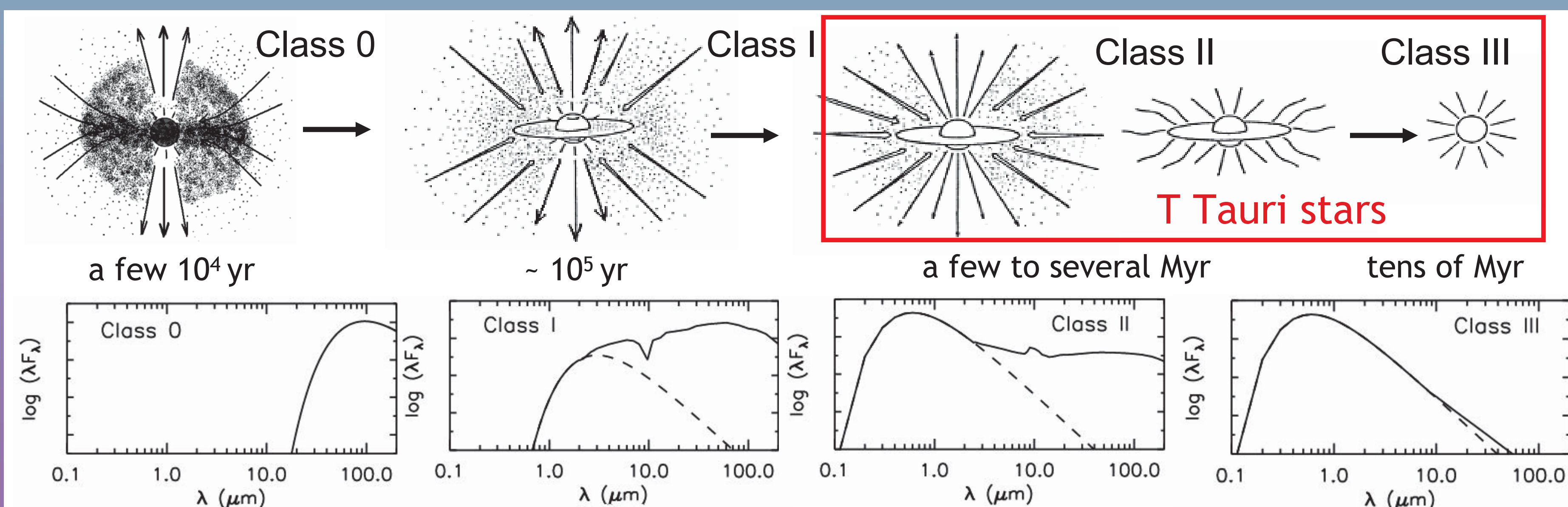
Barnard 68
(radius ~ 10000 AU;
Alves et al. 2001)

embedded protostar

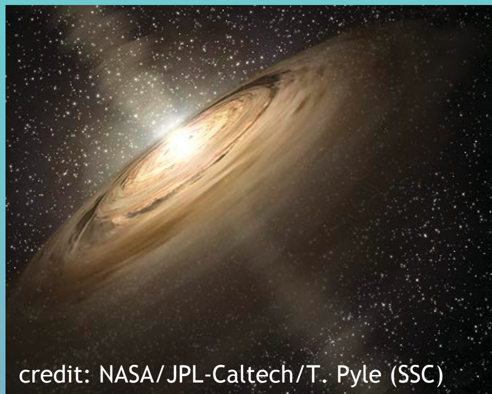


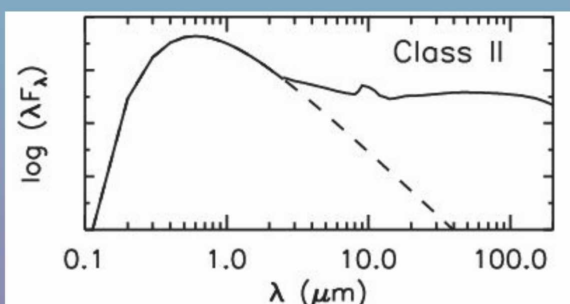
Solar System
(NASA/JPL)

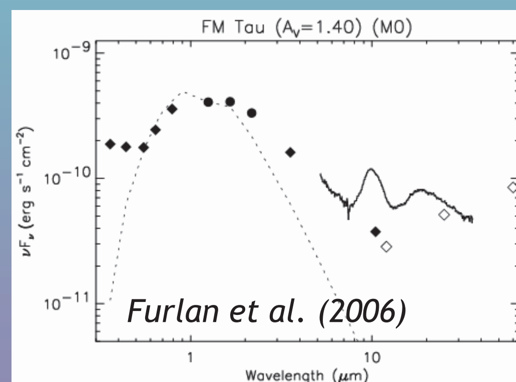
main-sequence star
with planetary system

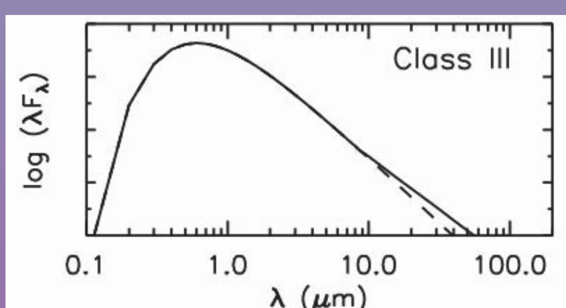


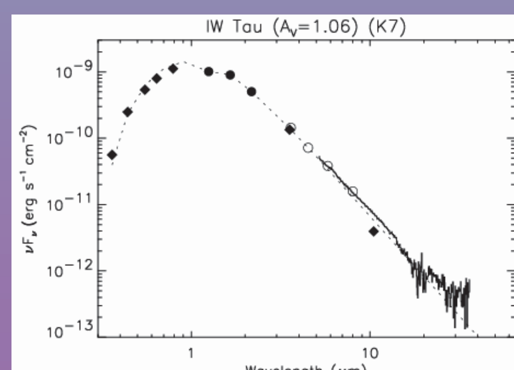
T Tauri Stars











classical T Tauri stars (CTTS):

Class II objects

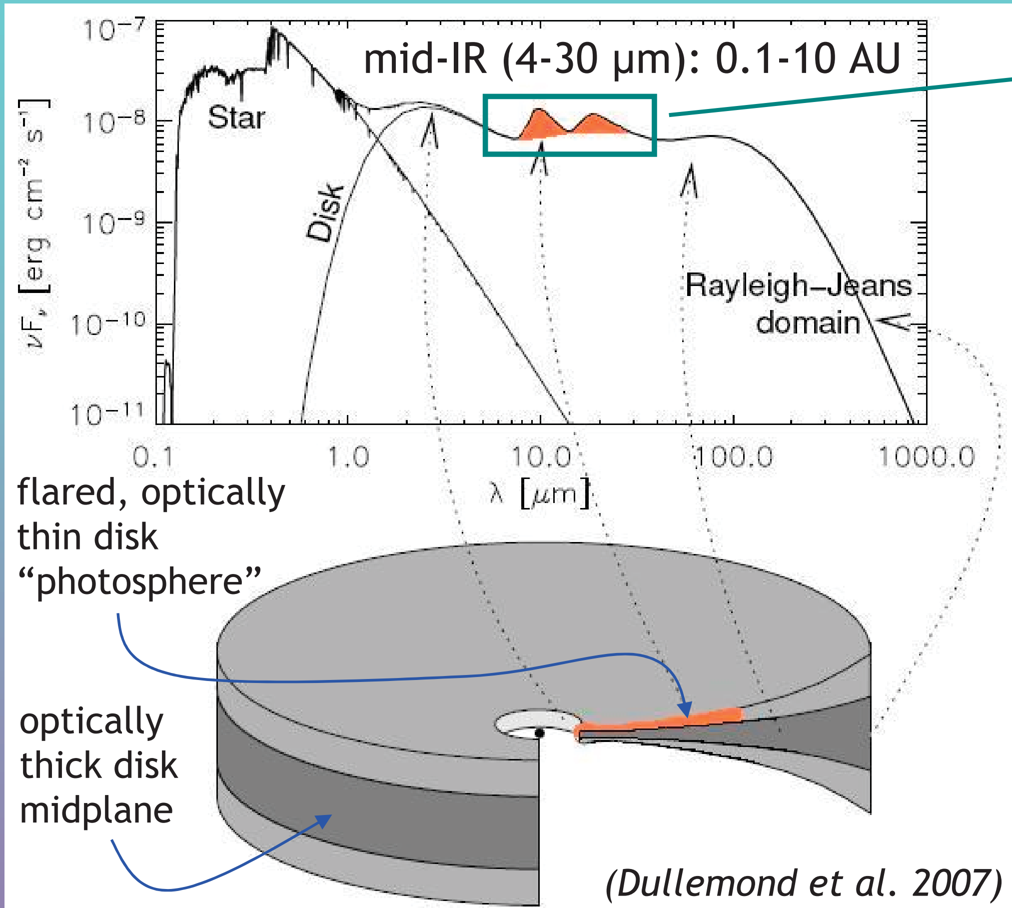
primordial, gas-rich accretion disk

weak-lined T Tauri stars (WTTS):

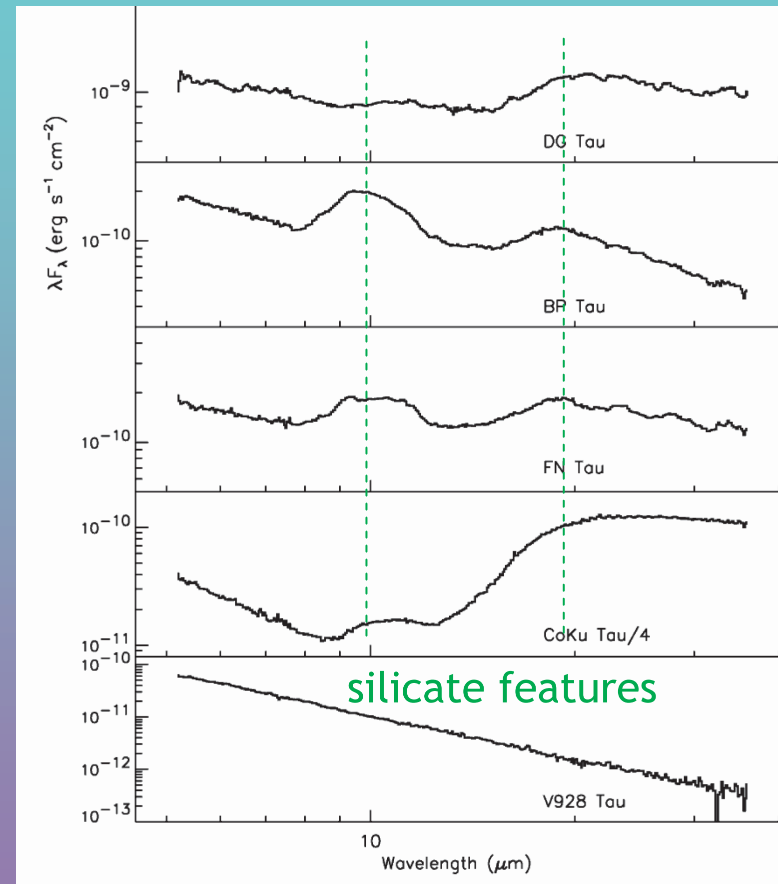
Class III objects, few Class II

passive primordial disk, or no disk

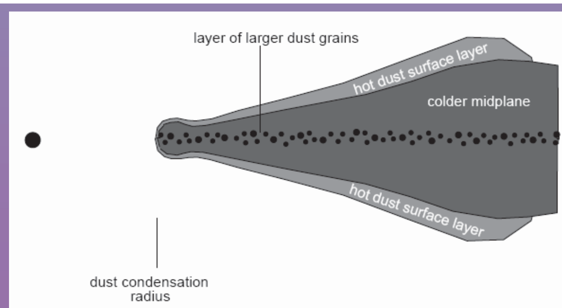
T Tauri Disk Structure and Emission



Spitzer IRS spectra (5-37 μm):



dust structure:



T Tauri Stars: Evolution

dissipation of primordial disk material $\Rightarrow$ decrease of infrared excess over time

❖ accretion of material onto the star

❖ grain growth and settling towards the midplane

$\Rightarrow$ SED slope becomes steeper, silicate feature becomes weaker, infrared excess decreases

❖ MRI-induced inner disk draining

$\Rightarrow$ mass accreted from the inner disk wall; disk dissipated from inside out

❖ photoevaporation

$\Rightarrow$ mass lost due to photoevaporative flow; low mass accretion rate and very low disk mass (depend on L_X); formation of an inner disk hole

❖ formation of larger bodies, planets

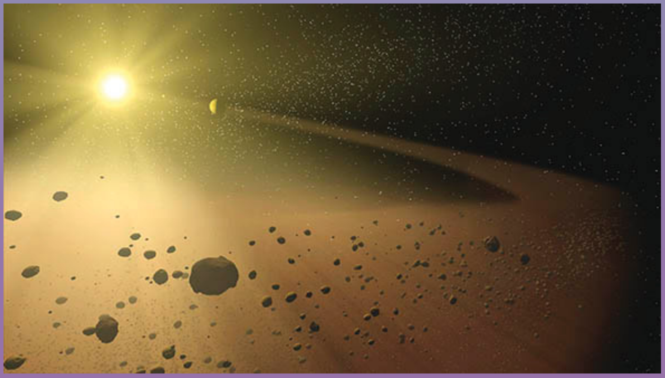
★ core accretion (several Myr)

★ disk gravitational instabilities (<1000 years)

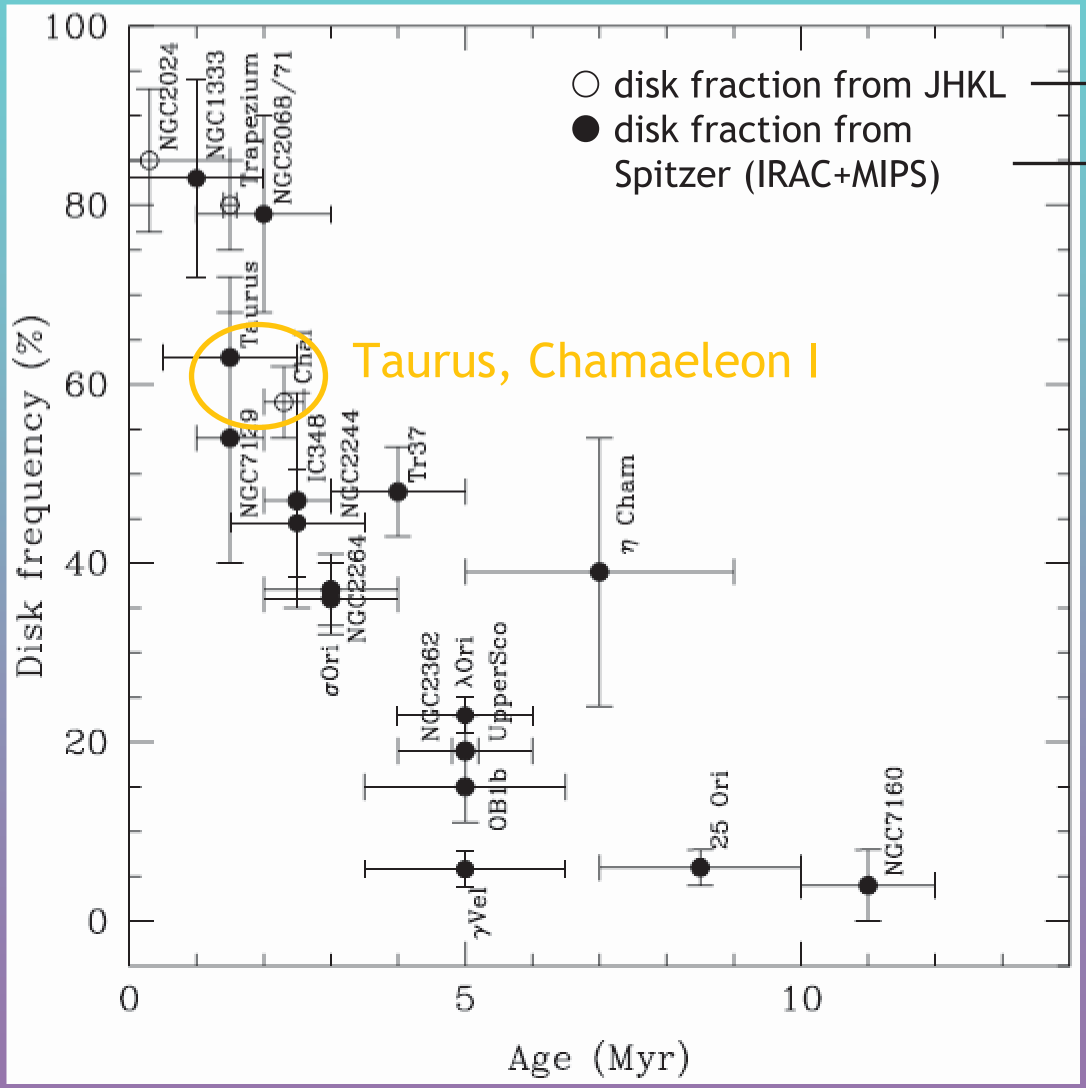
$\Rightarrow$ grain growth, disk gap/hole formation, remnant mass accretion and outer disk

❖ optically thin (debris) disk

$\Rightarrow$ no mass accretion, very low disk mass and very small infrared luminosity



Disk Fractions from 1 to 10 Myr



→ 1.25-3.5 μm

→ 3.6-8 μm, 24 μm

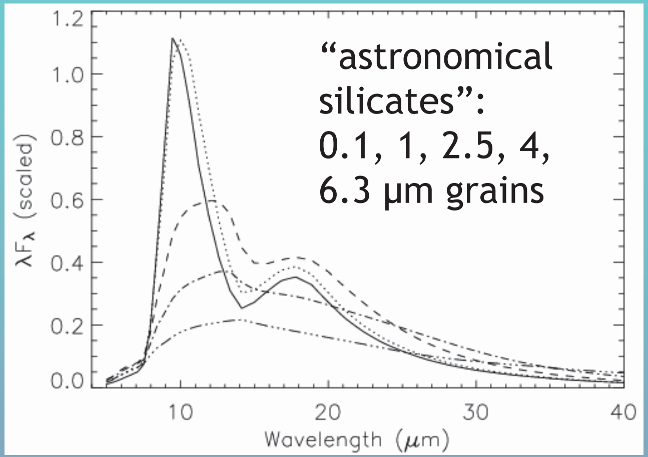
(disk fraction depends somewhat on wavelength range)

Hernandez et al. (2008)

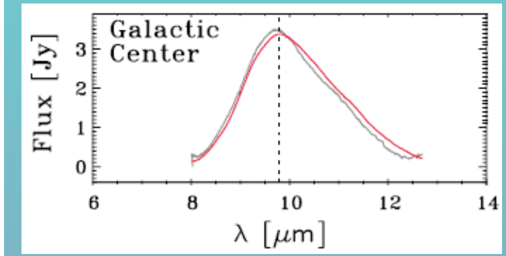
⇨ disk dissipation in ~ 10 Myr

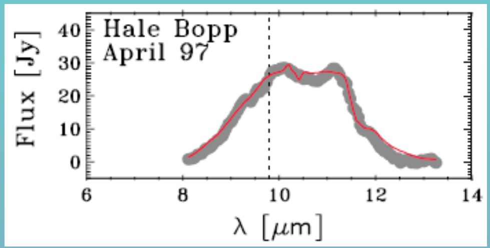
Dust Growth, Processing, and Settling

Growth and crystallization of amorphous silicate grains:



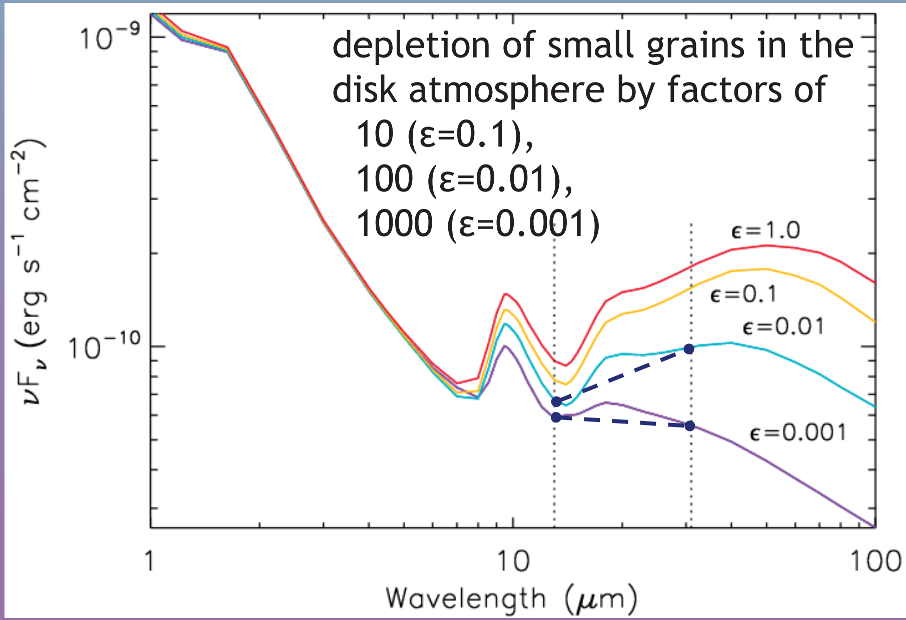
Draine & Lee (1984)

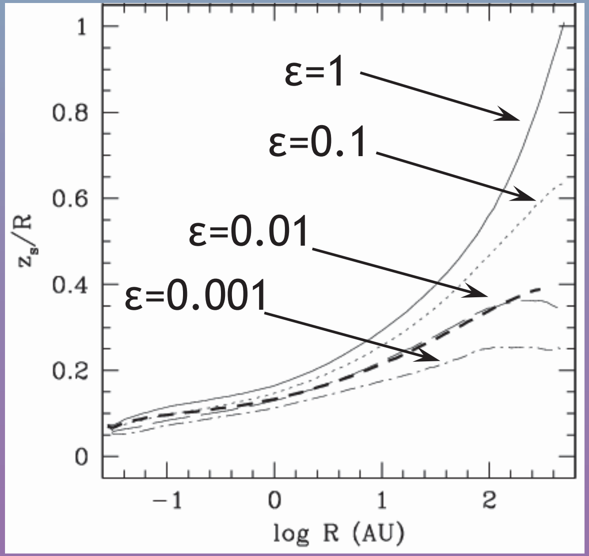




Bouwman et al. (2001)

Accretion disk models with various amounts of dust settling:



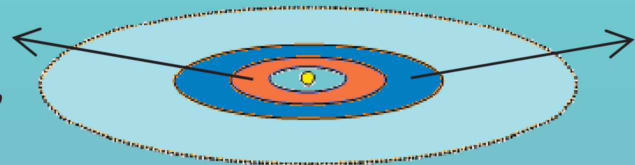


Furlan et al. (2005b), D'Alessio et al. (2006)

Disk Evolution with the IRS: Dust Processing

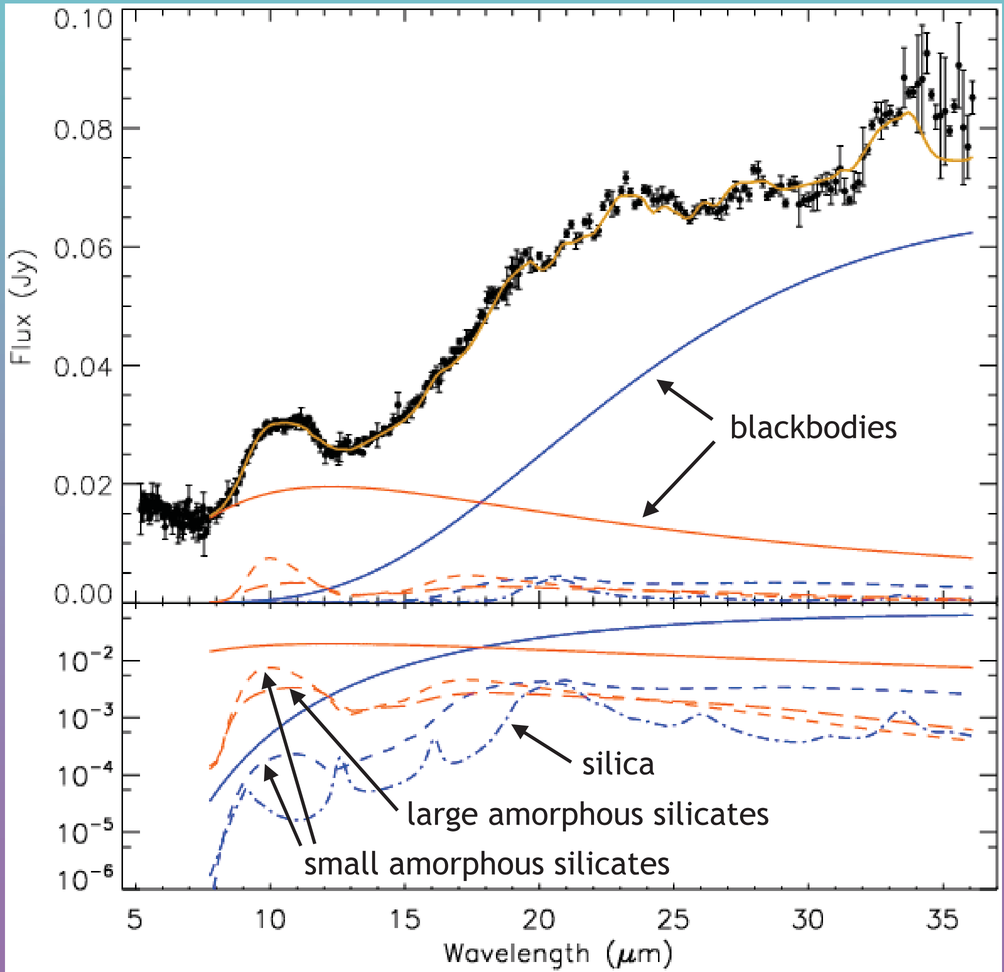
2-temperature dust feature fits of 65 T Tauri star spectra in Taurus:

warm, inner disk (~0.5 AU, ~600 K)



cool, outer disk (~5 AU, ~150 K)

Sargent et al. (2009b)



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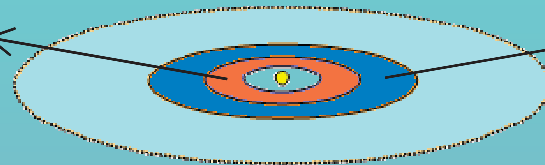

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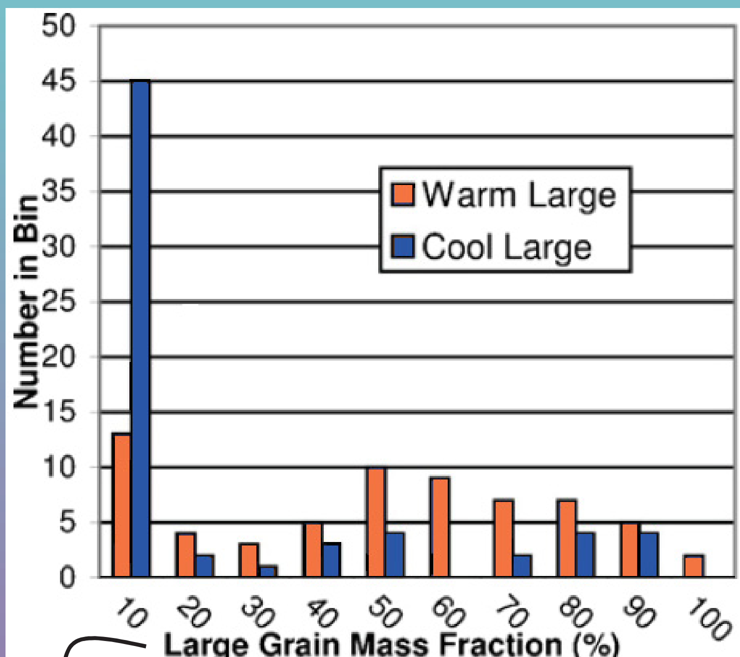
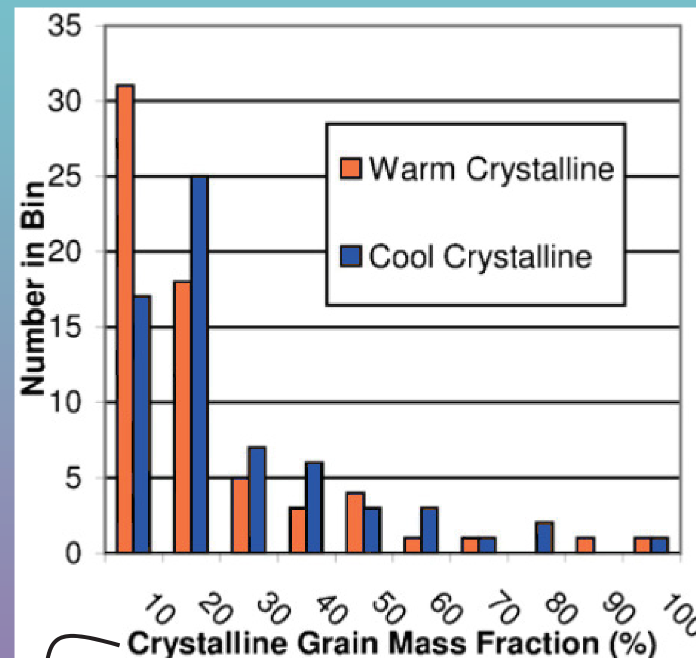
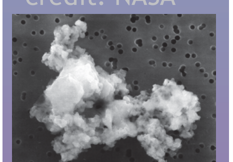




credit: NASA

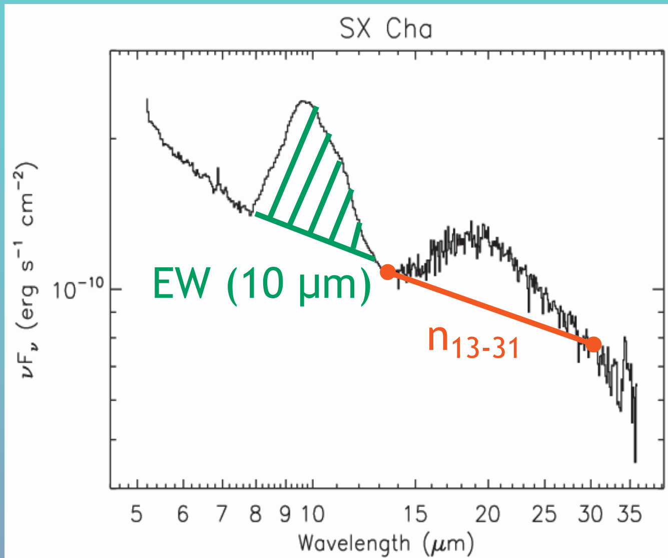


amorphous olivine and pyroxene;
5 μm porous spheres with 60% vacuum

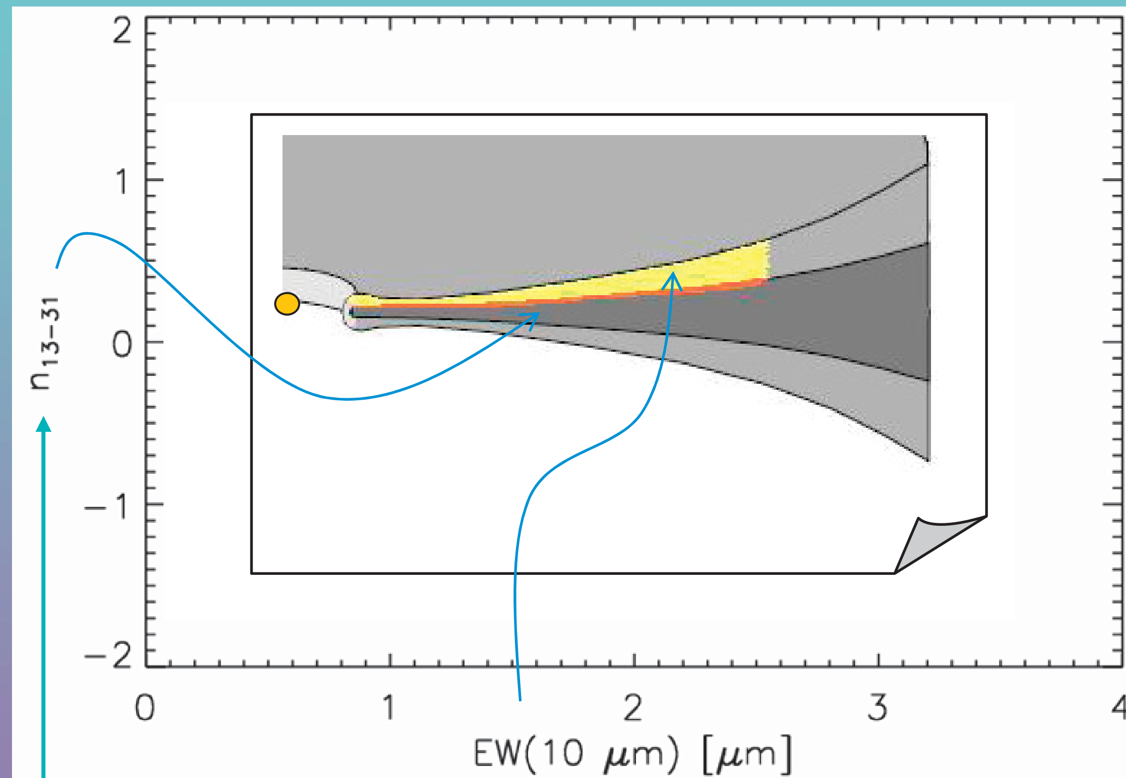
forsterite, enstatite, silica

dispersion in individual system's dust properties
⇒ no steady dust processing and evolution
→ radial mixing; turbulence; planet formation clearing processed dust

Disk Evolution with IRS: SED Slope and 10 μm Feature



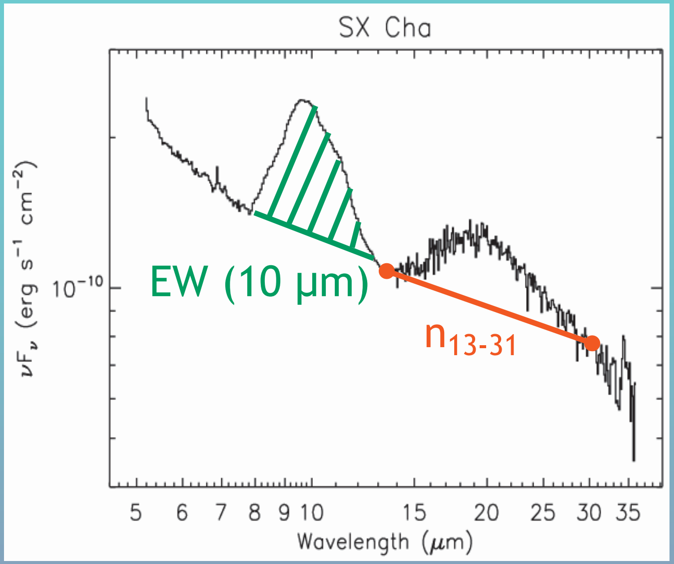
Watson et al. (2009), Furlan et al. (2009a)



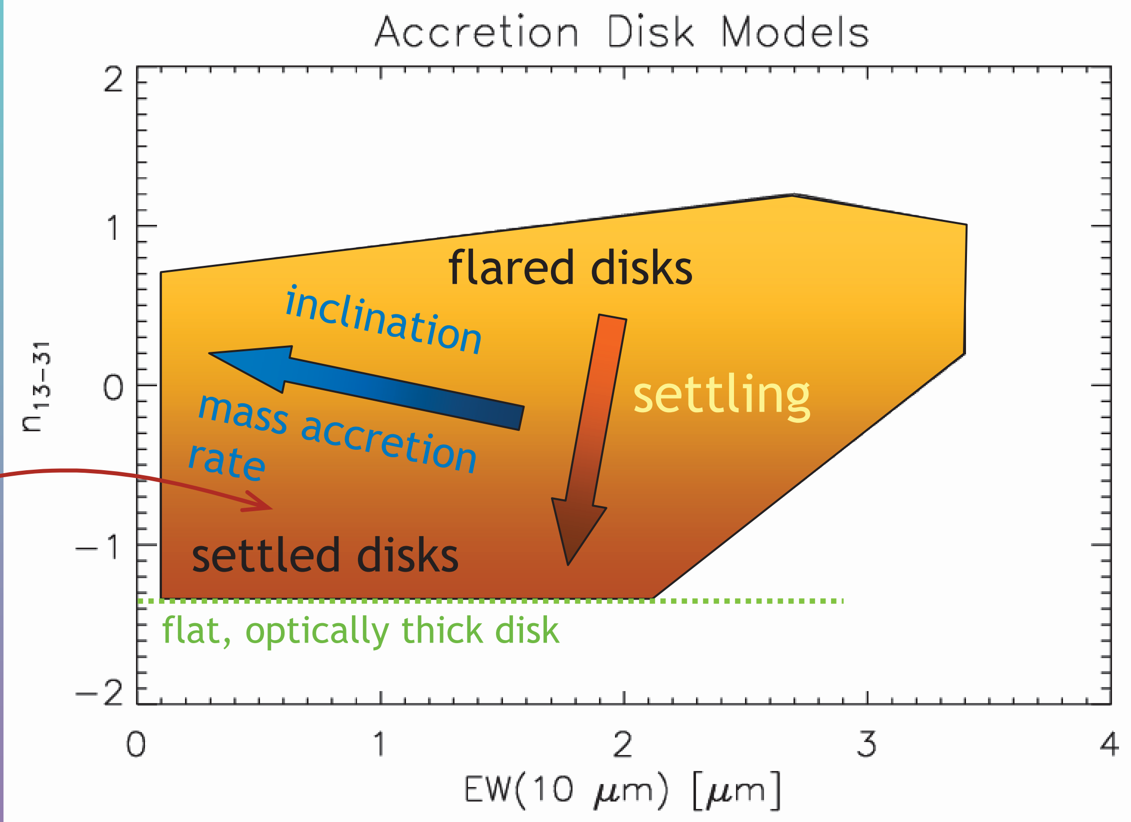
13-31 μm spectral index: degree of dust settling

10 μm feature equivalent width: optically thin dust mass per area of optically thick disk

Disk Evolution with IRS: SED Slope and 10 μm Feature

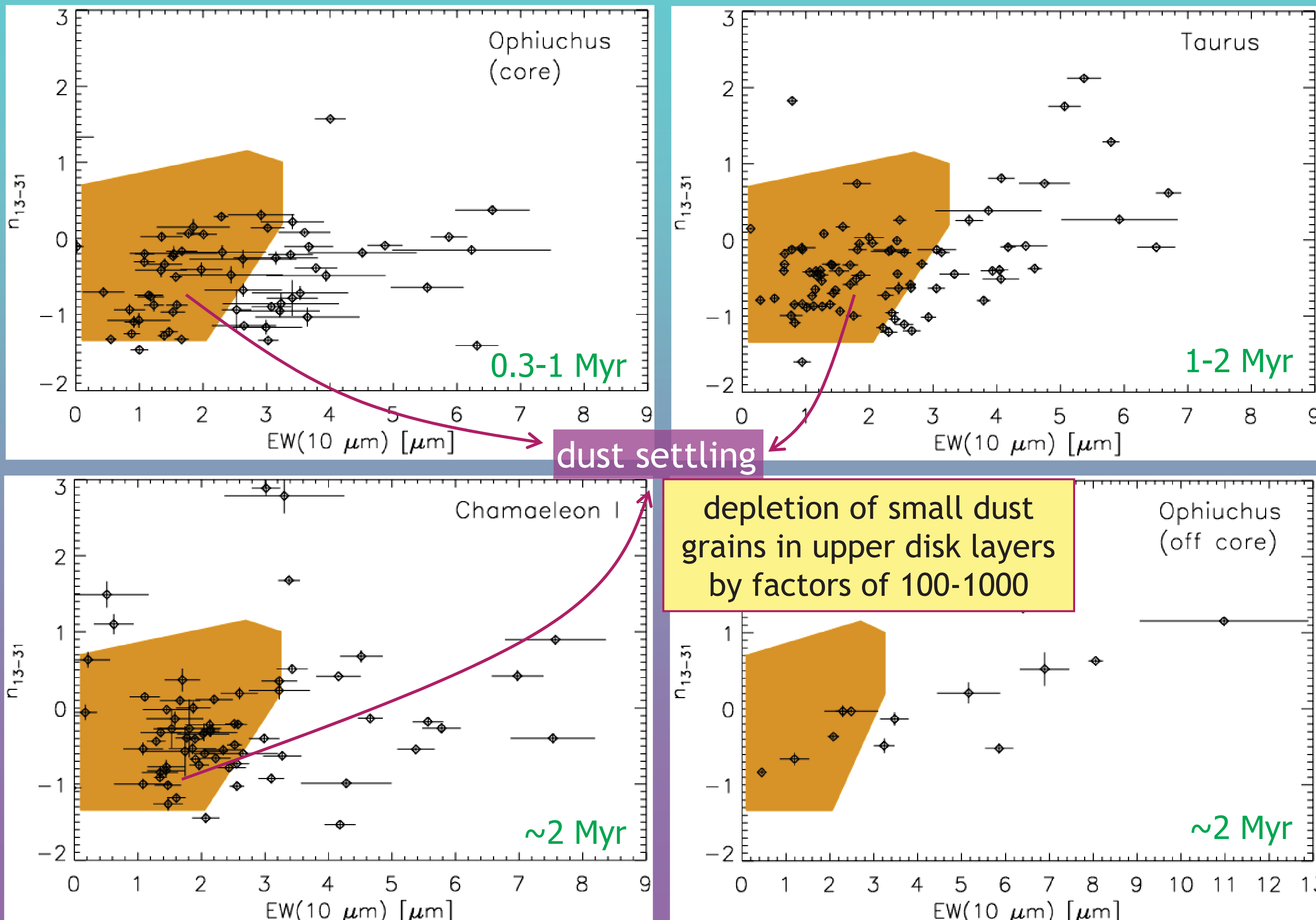


Watson et al. (2009), Furlan et al. (2009a)

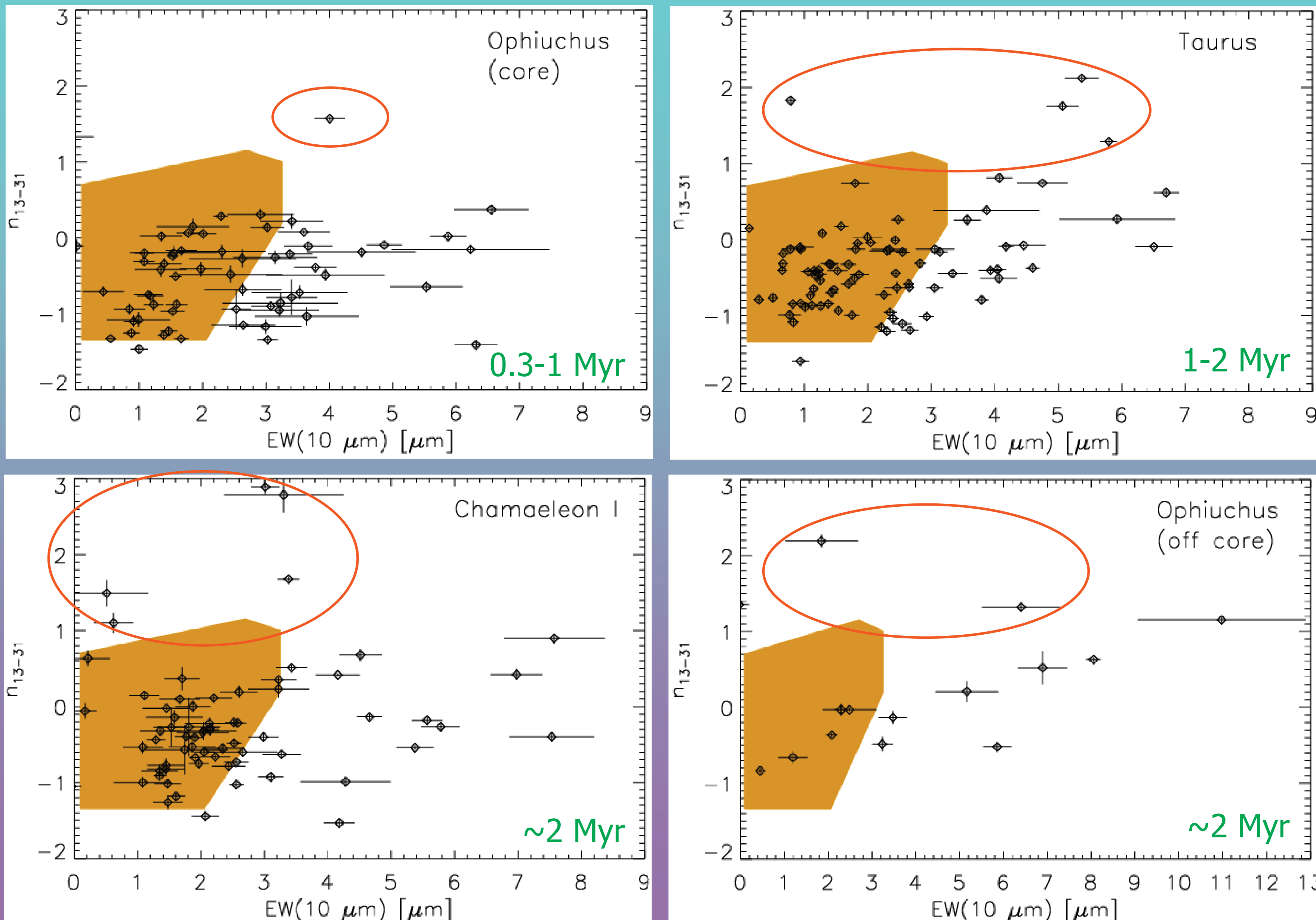


spread from model calculations (full protoplantary accretion disks)

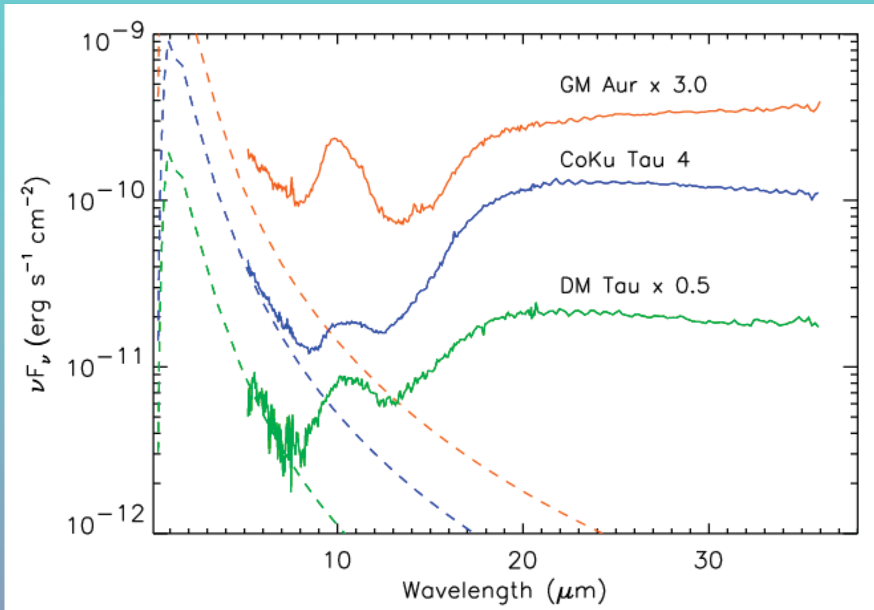
Disk Evolution in Oph, Tau, Cha

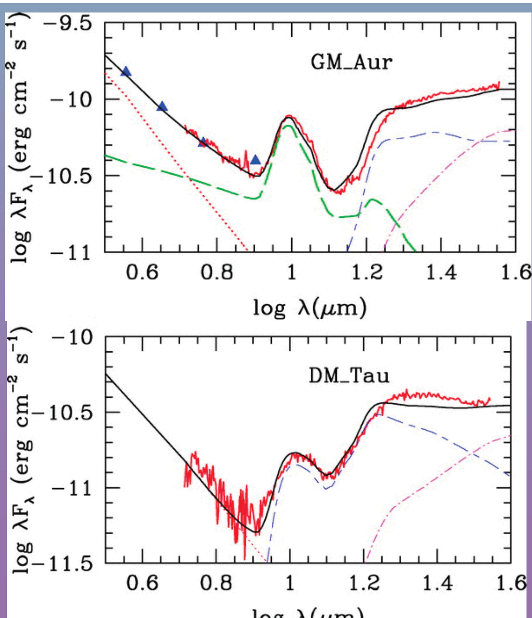


$n_{13\text{-}31}$ Outliers



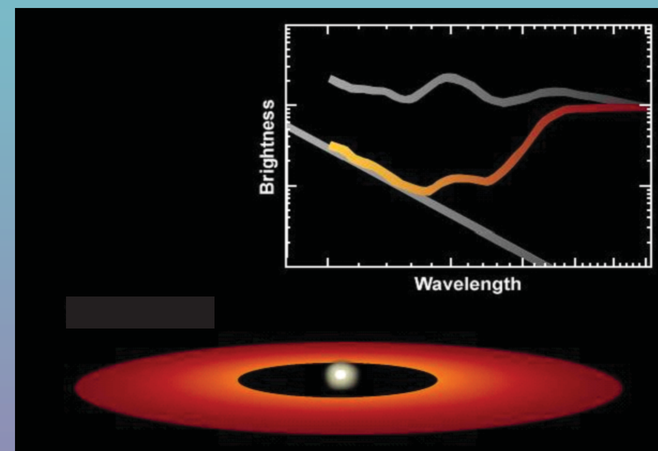
$n_{13\text{-}31}$ Outliers: Transitional Disks





Calvet et al. (2005)

- large excess > 8 µm, steep SED rise
  → single-temperature blackbody
- little/no excess < 8 µm
  → small dust grains are depleted
  from the inner regions of the disk



credit: NASA/JPL-Caltech/ D. Watson (University of Rochester)

fraction of transitional disks:
a few % at an age of 1-2 Myr,
but ~15-20 % at an age of >3 Myr
⇒ slower transition timescale for older (>3 Myr) — and lower-mass — objects?
→ different disk clearing mechanisms

Furlan et al. (2009a), Muzerolle et al. (2010)

Interpreting Transitional Disks

decrease of infrared excess over time

- → accretion of material onto star
- → grain growth and settling towards midplane
- → planet formation
- → photoevaporation
- → MRI-induced inner disk draining

disk clearing from inside out

inner disk hole with a sharp edge

< 1 Myr

planet formation

core accretion ~ a few Myr: grain growth, settling; disk gap; remnant outer disk; remnant mass accretion

gravitational instability < 1000 yr: massive disk (M_{disk} > ~ 0.1 $M_\star$)

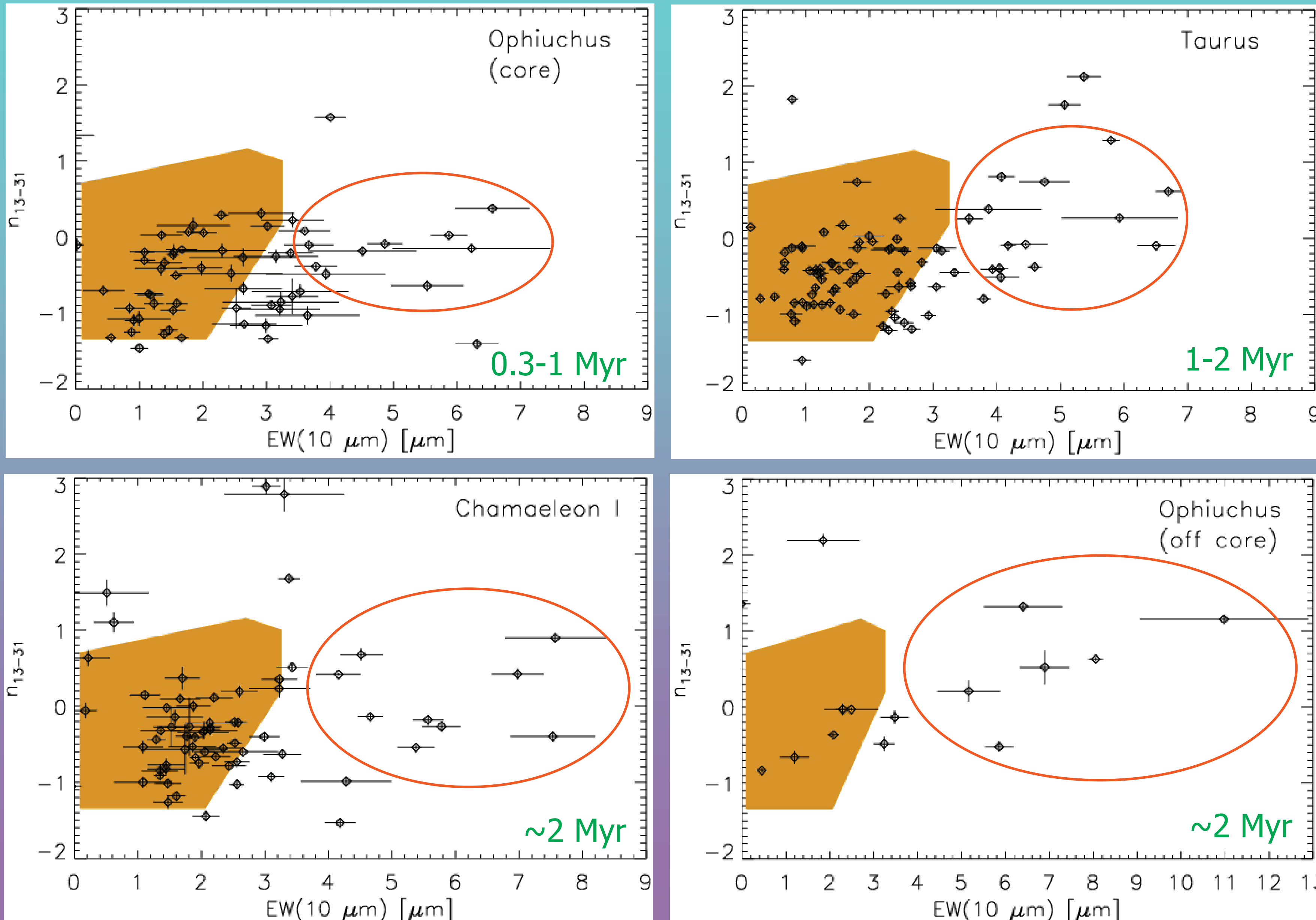
MRI disk clearing ~ 1 Myr: remnant outer disk; remnant mass accretion

photoevaporation ~ 0.1 Myr: vanishing outer disk; very low/no mass accretion; low L_X

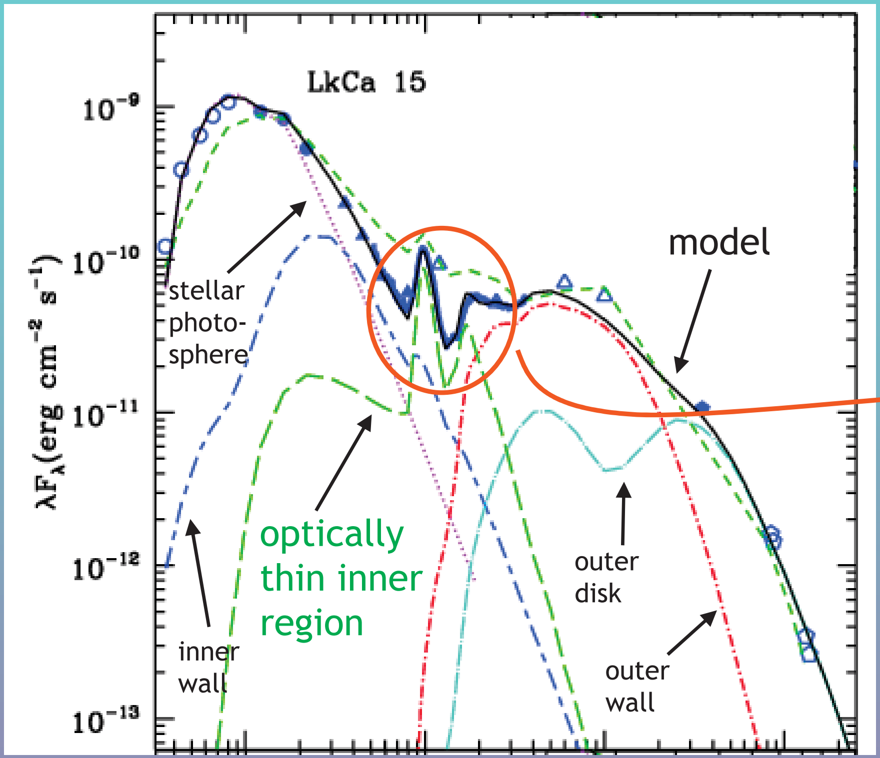
remnant outer disk; remnant mass accretion; high L_X

close binary → stable circumbinary disk

EW(10 μm) Outliers

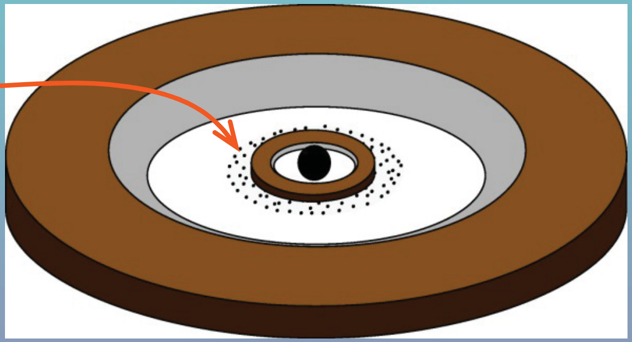


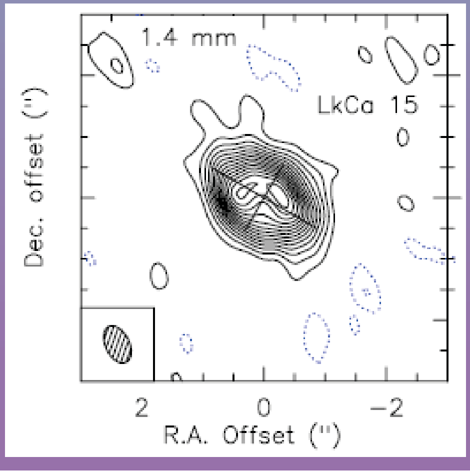
"Pre-Transitional Disk": LkCa 15



SED model: inner wall at ~ 0.1 AU, optically thin inner region at 0.15-5 AU, outer wall at 46 AU

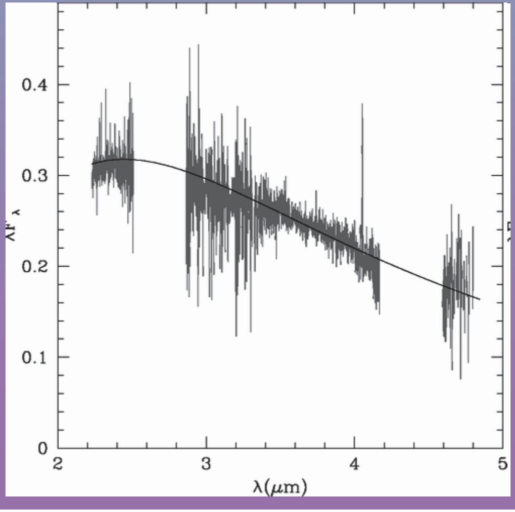
Espaillat et al. (2007b)





1.4 mm image $\Rightarrow$ ~ 50 AU inner cavity

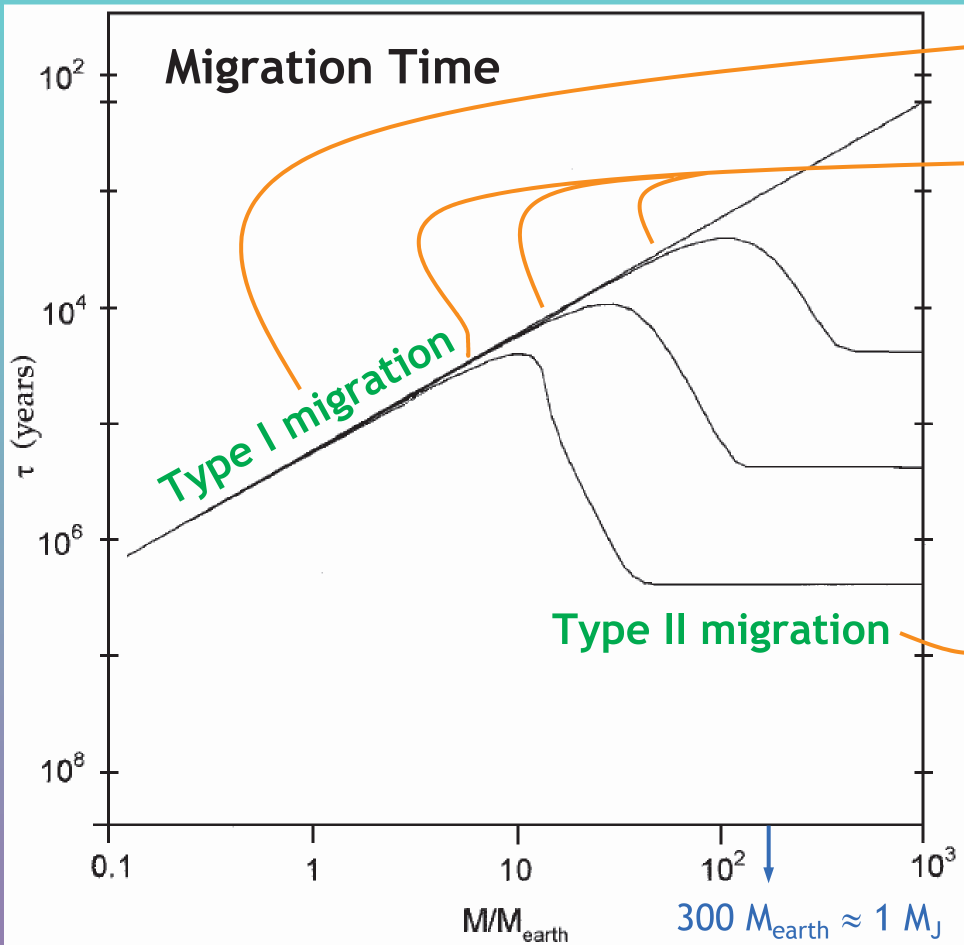
Pietu et al. (2006)



near-infrared excess fit with a 1600 K blackbody $\Rightarrow$ inner wall emission

Espaillat et al. (2008)

Planet Formation and Disk Gaps



Ward (1997)

(lower-mass) protoplanet drifts relative to the disk

planet is massive enough to open up a gap

protoplanet migrates on the viscous timescale (i.e., with the disk)

inner disk gap caused by a (massive) planet

→ filtration of dust particles at the outer edge of the disk gap (pressure gradient)

→ gas accretion across the gap (~10% of accretion rate outside the gap), small grains (≤ 1 μm for 1 M_J planet) coupled to gas

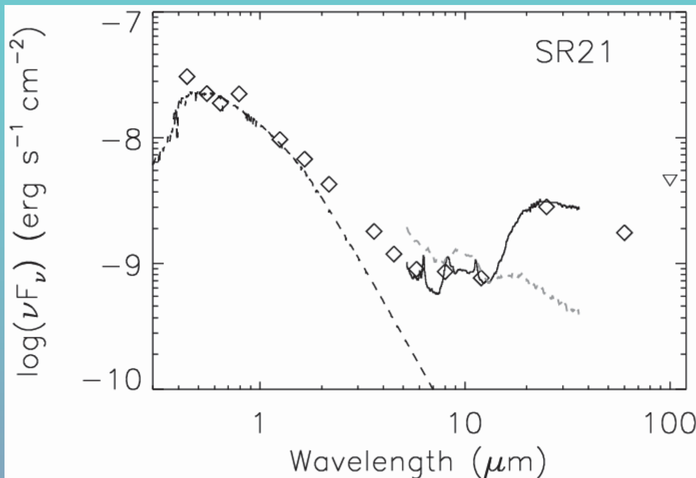
→ accumulation of large dust grains at the outer gap edge

credit: NASA/JPL-Caltech/T. Pyle (SSC)

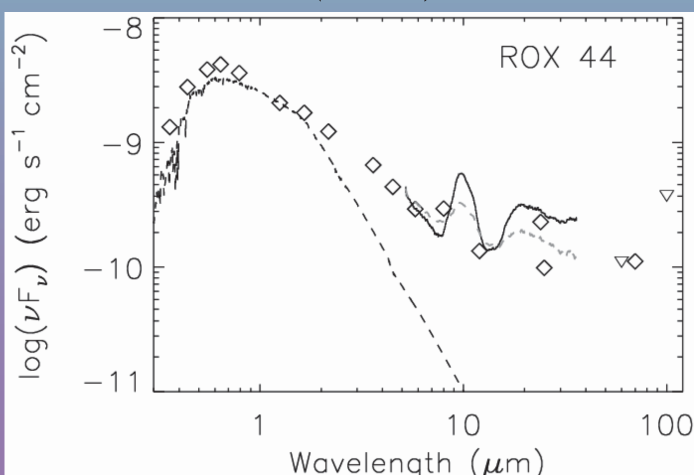
Rice et al. (2006), Lubow & D'Angelo (2006)

Other Disks with Gaps?

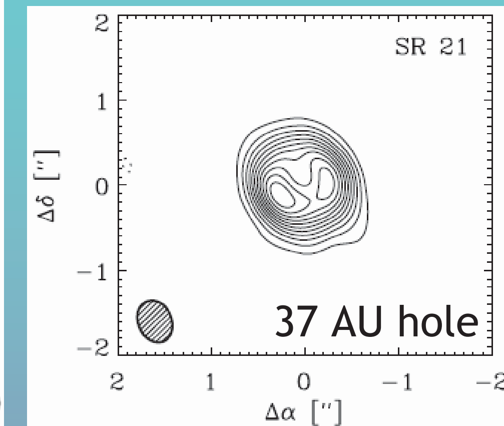
SEDs, with IRS spectrum:



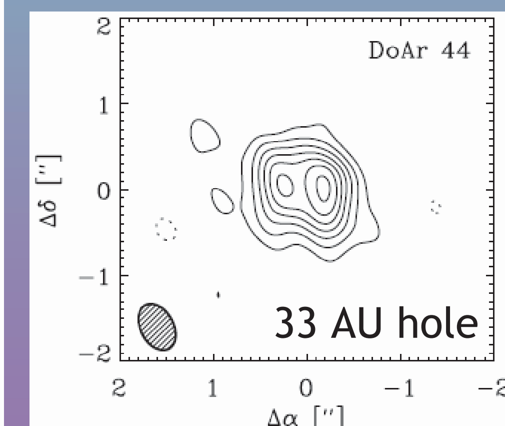
Furlan et al. (2009a)



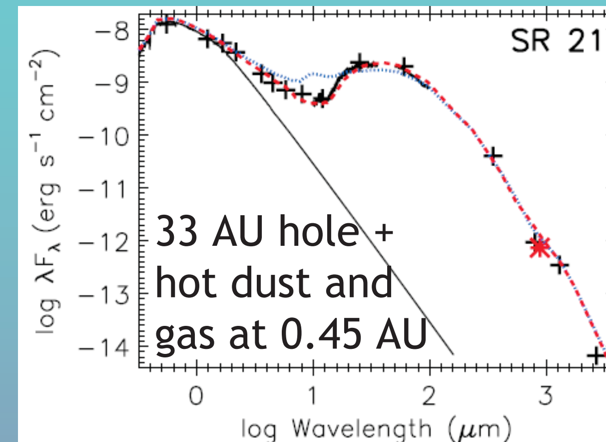
870 μm continuum images:



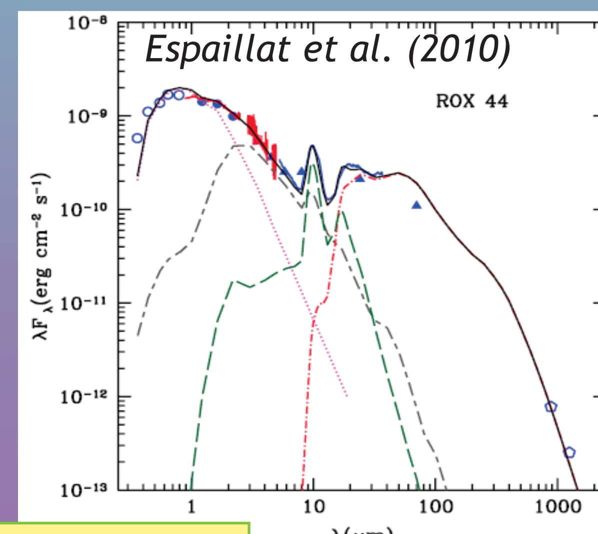
Andrews et al. (2009)



models:



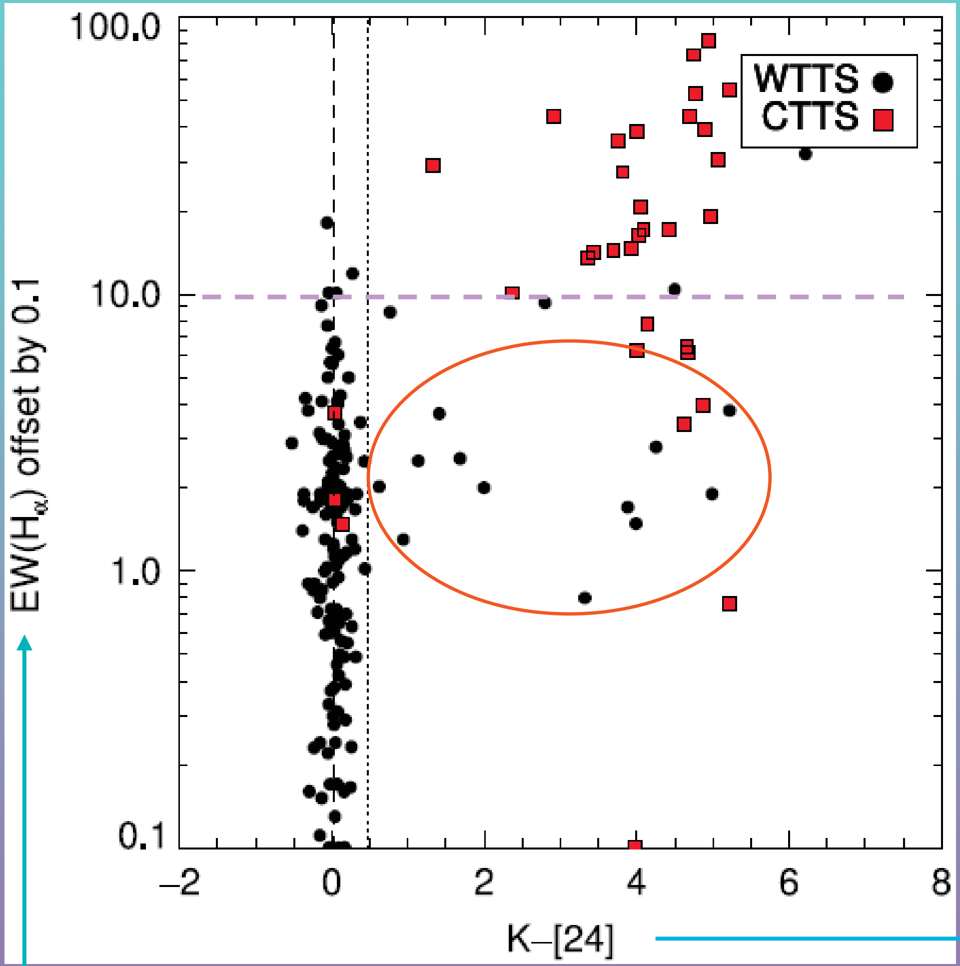
Brown et al. (2009)



Espaillat et al. (2010)

fraction of EW(10 μm) outliers: 20-30 % at an age of 1-2 Myr
→ evidence for disk gaps and planet formation?

Late Stages of Disk Dissipation



Wahhaj et al. (2010)

- classical T Tauri stars (CTTS): accretion disks
  - → strong Hα emission from the accretion flow
  - → infrared excess from the disk
- weak-lined T Tauri stars (WTTS): no accretion signatures
  - → weak Hα emission line from stellar chromosphere
  - → typically no infrared excess, but several outliers

~ ratio of fluxes at 24 and 2.2 μm: measure for infrared excess

strength of the Hα emission line: measure for mass accretion onto the star

WTTS with Infrared Excesses

- final disk dissipation stage?
  - → accreting at very low or variable levels?
  - → not accreting, short-lived remaining dusty disks?
  - → optically thick disks or optically thin disks?
  - → grain growth and settling?
  - → inner disk hole formation?

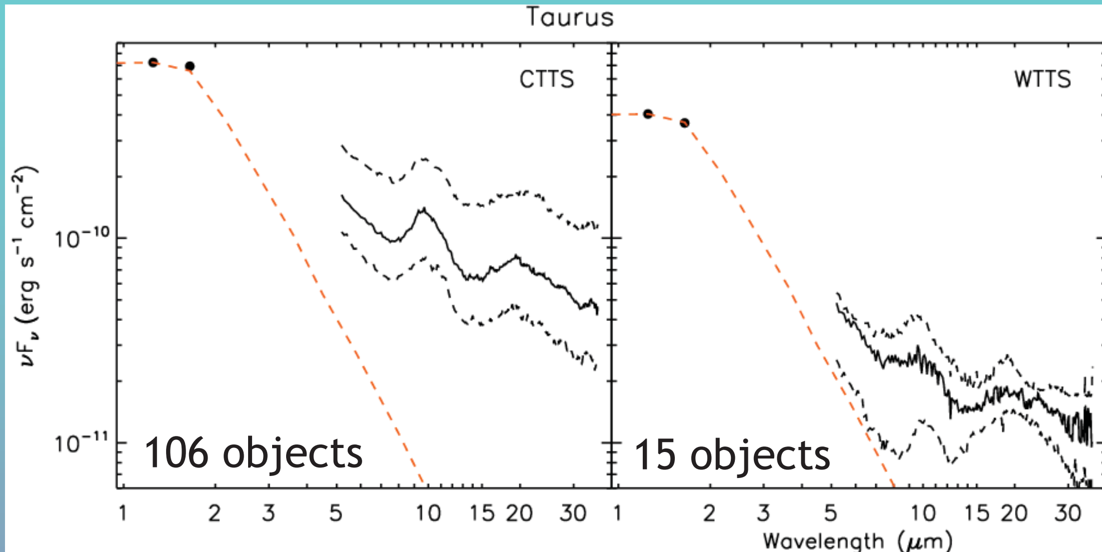
WTTS disk fractions in 1-3 Myr-old clusters (based on IRAC): ~ 20% *(Cieza et al. 2007, Wahhaj et al. 2010)*

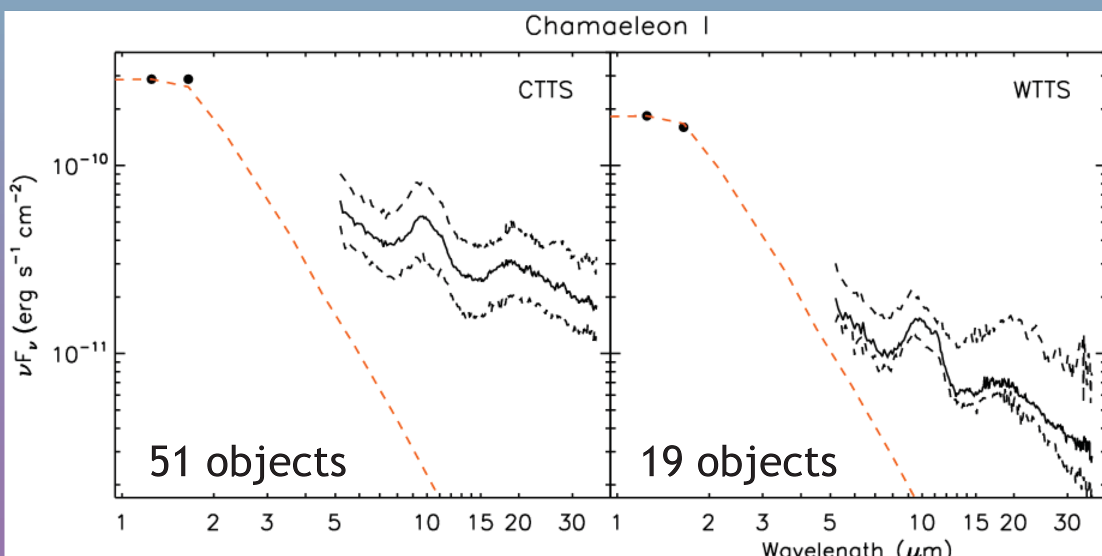
WTTS disk fraction in IC 348 (2-3 Myr old) (based on IRAC): ~35% *(Lada et al. 2006)*

Taurus (1-2 Myr old, ~ 350 YSOs):
~200 T Tauri stars with infrared excesses (at ≤ 24 μm) and Spitzer data
(151 of which have 5-37 μm IRS spectra):
68% are CTTS, 14% are WTTS, 18% are not classified

Chamaeleon I (~ 2 Myr old, ~ 200 YSOs):
~100 T Tauri stars with infrared excesses (at ≤ 24 μm) and Spitzer data
(88 of which have 5-37 μm IRS spectra):
56% are CTTS, 29% are WTTS, 15% are not classified

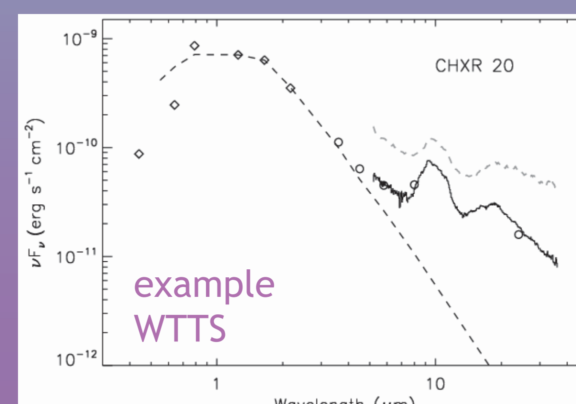
WTTS and CTTS Medians





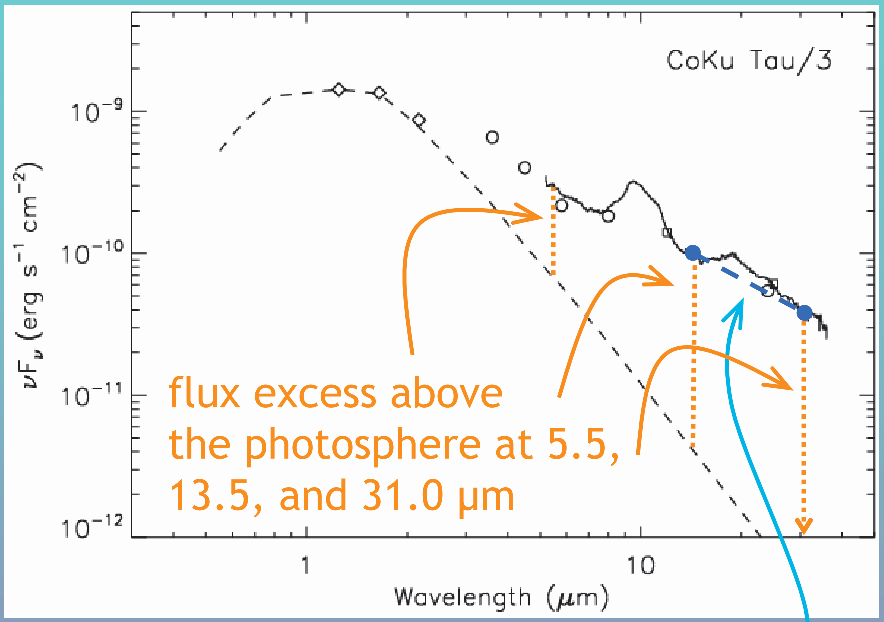
Median SEDs for CTTS and WTTS in Taurus and in Chamaeleon I
(K0-M6 spectral types)

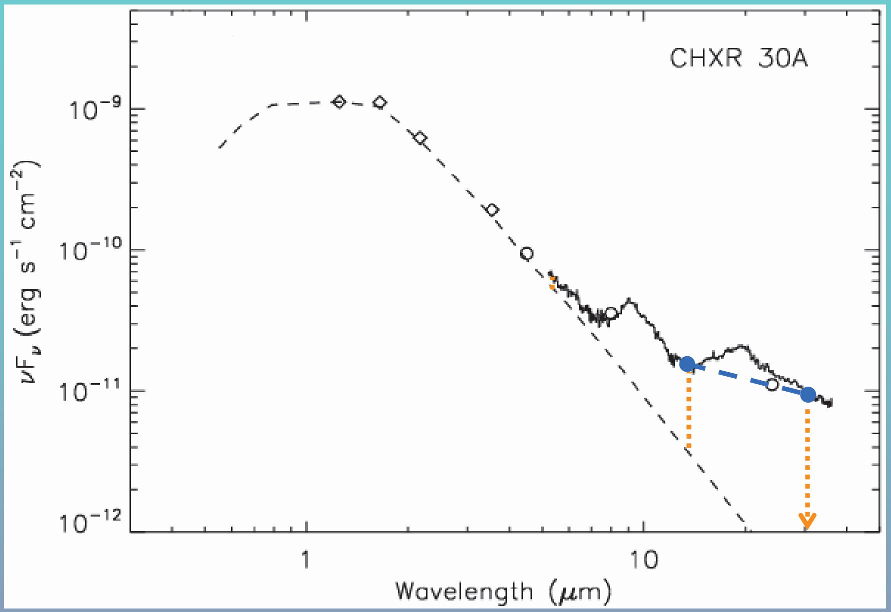
WTTS in with infrared excesses
→ low near-IR excess (< 6 μm),
weaker excess than CTTS
at all wavelengths
⇒ depletion of disk material,
especially in the inner disk

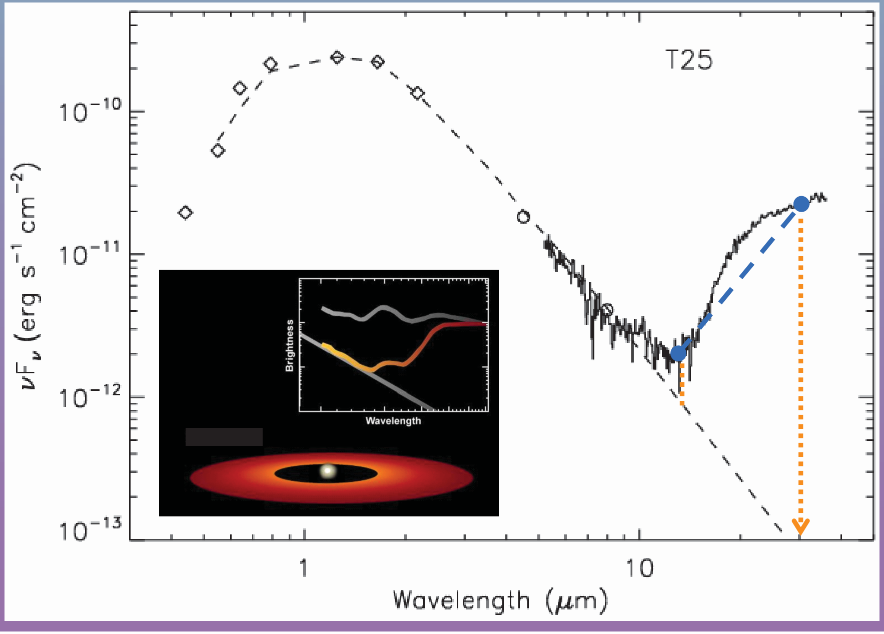


Furlan et al. (in prep.)

SED Slopes and Excess Emission

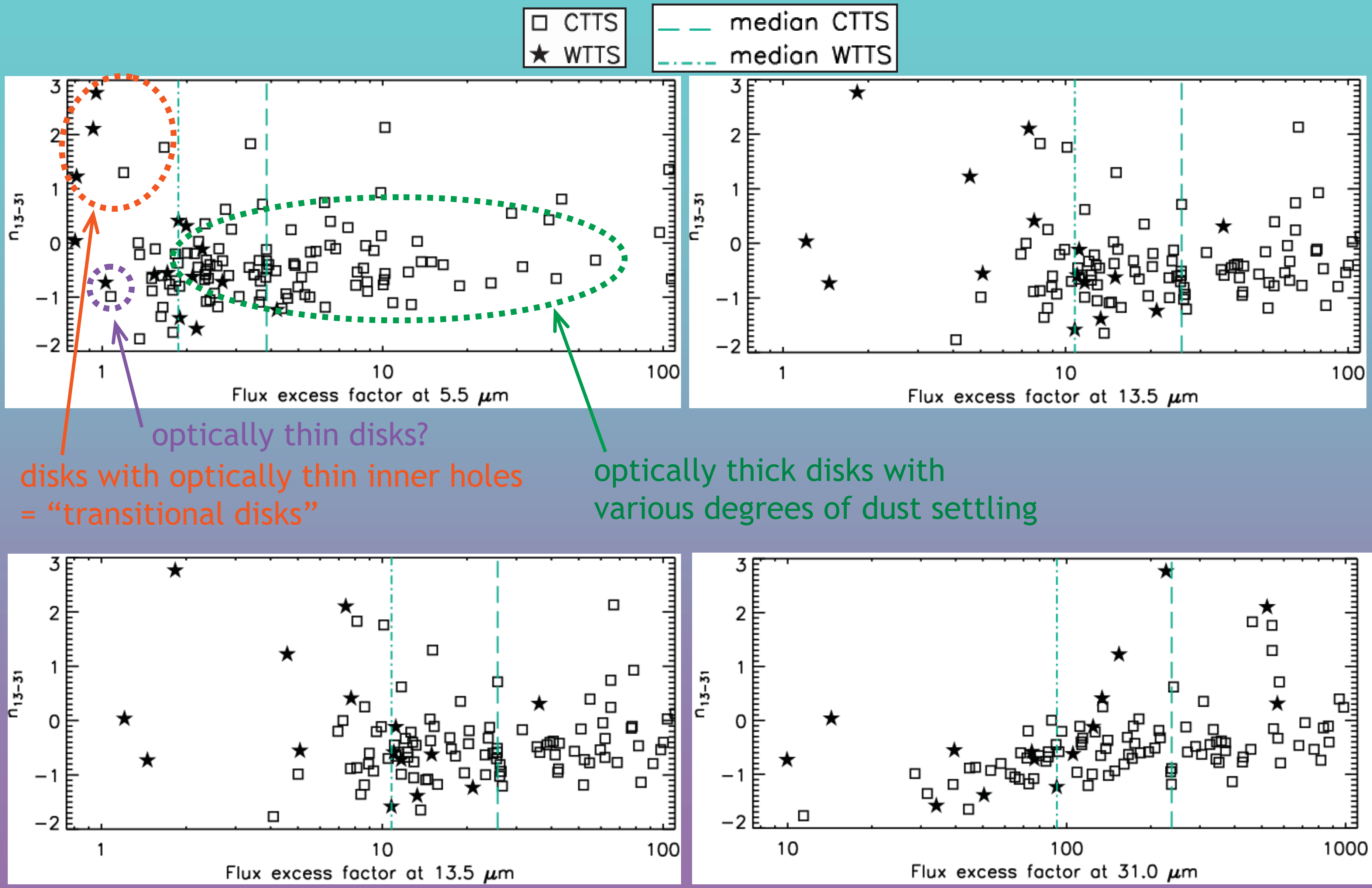




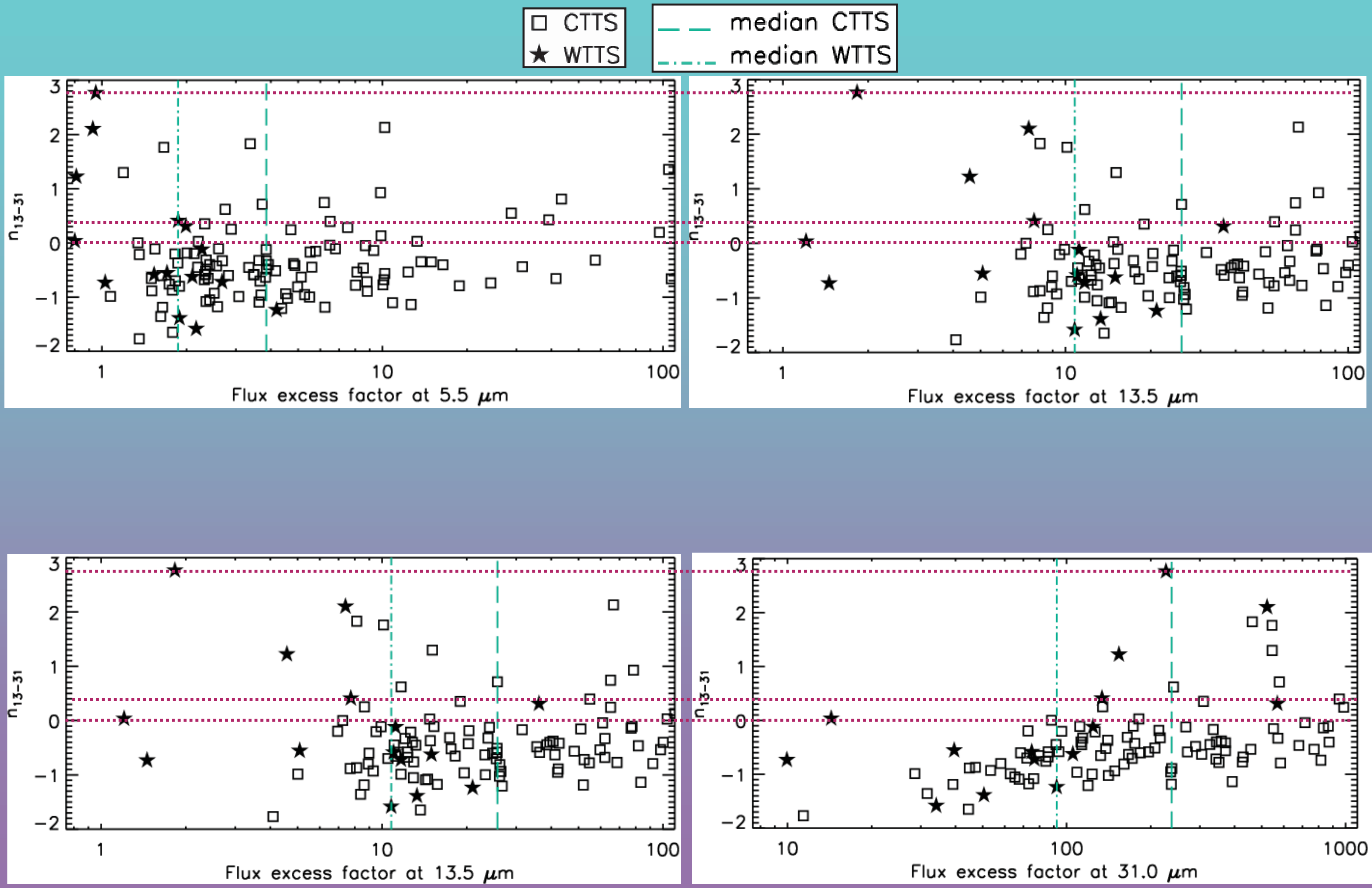


SED slope between 13 and 31 μm
⇒ degree of flaring of the disk,
vertical disk structure

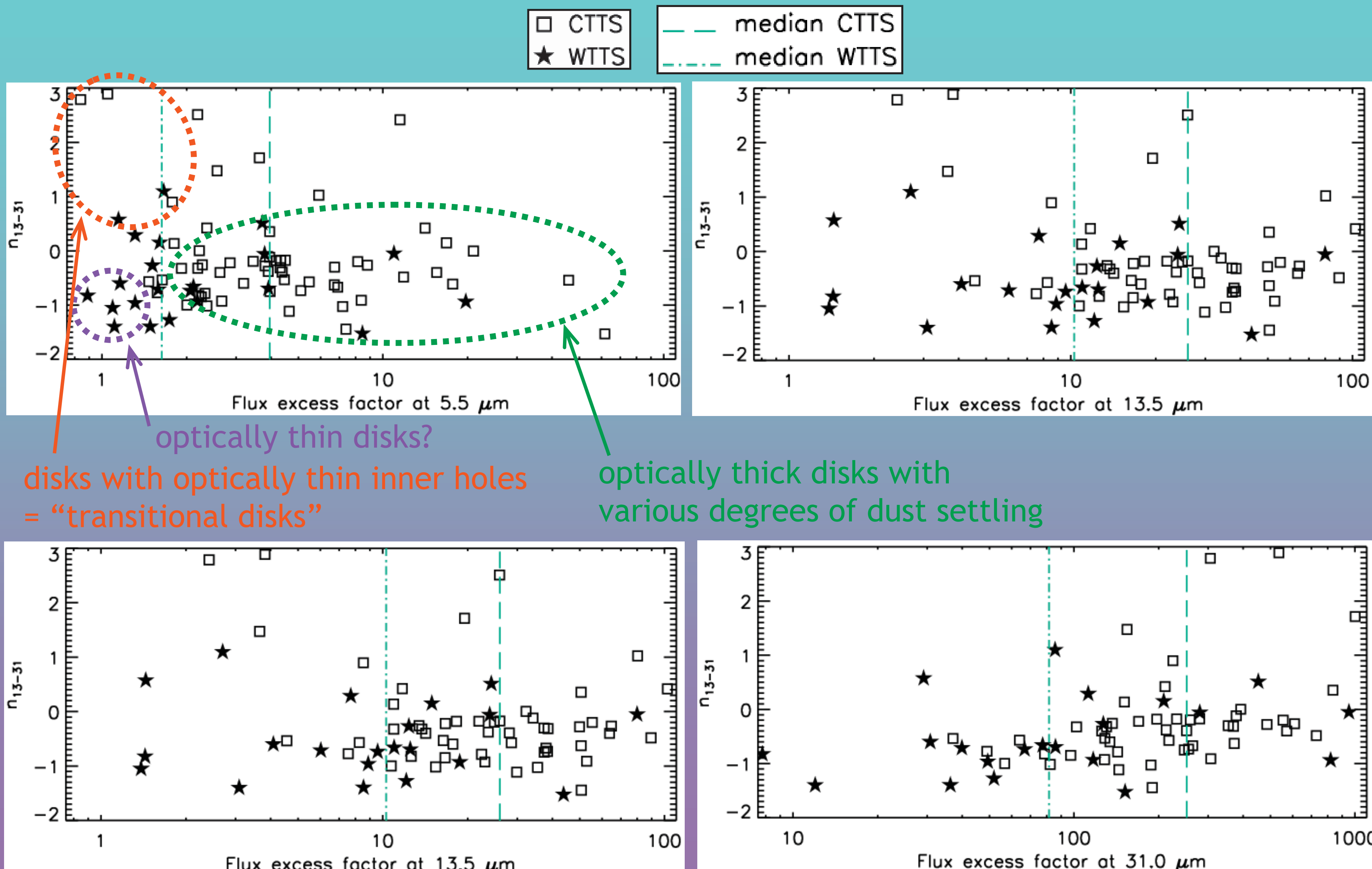
SED Slopes and Excess Emission: Taurus



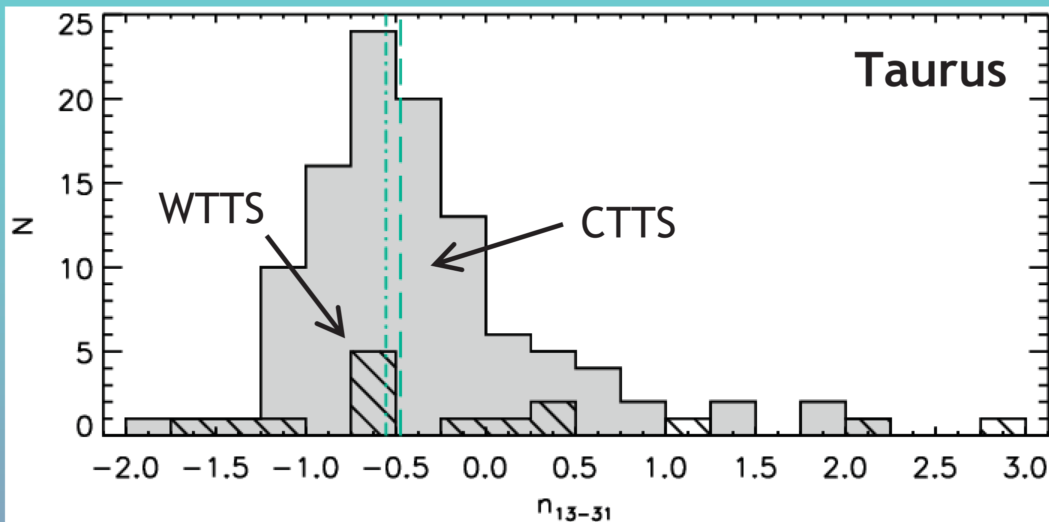
SED Slopes and Excess Emission: Taurus

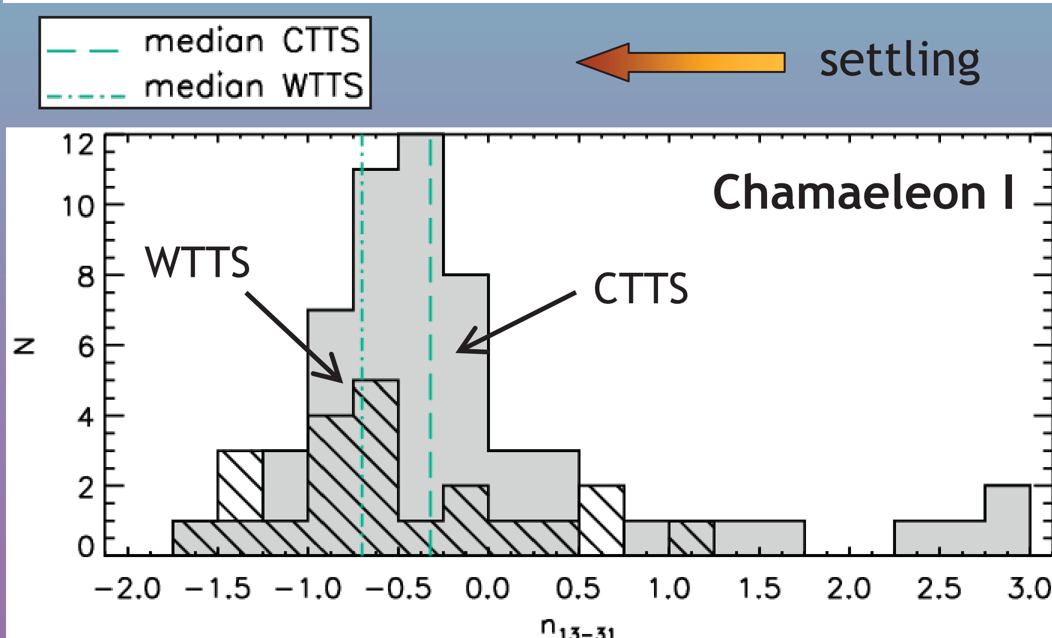


SED Slopes and Excess Emission: Chamaeleon I



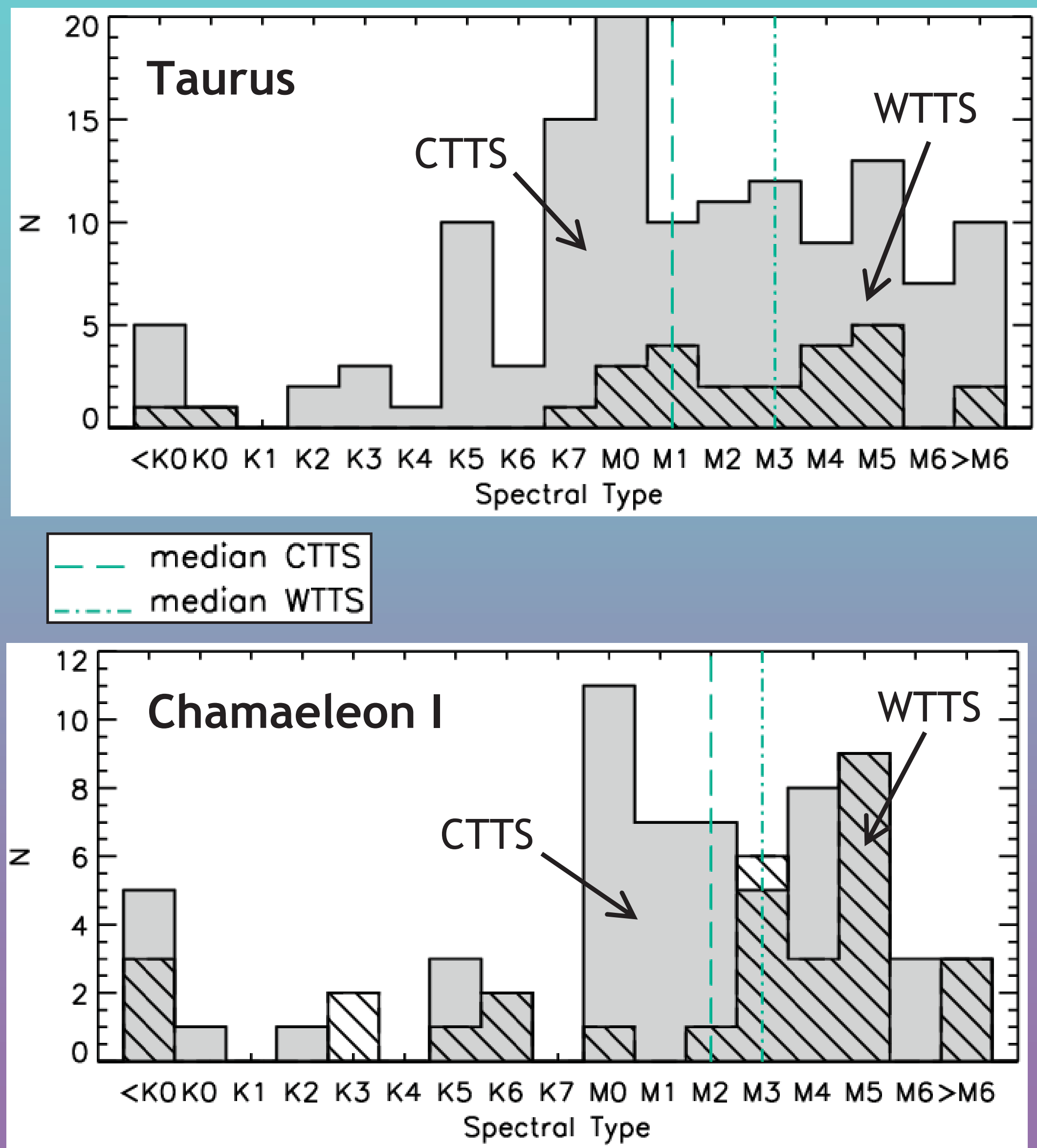
SED Slopes of CTTS and WTTS





CTTS and WTTS:
similar distribution of
13-31 μm spectral indices;
similar median values for
Taurus objects, but lower
median spectral indices for
Chamaeleon I WTTS
⇒ more settled disks

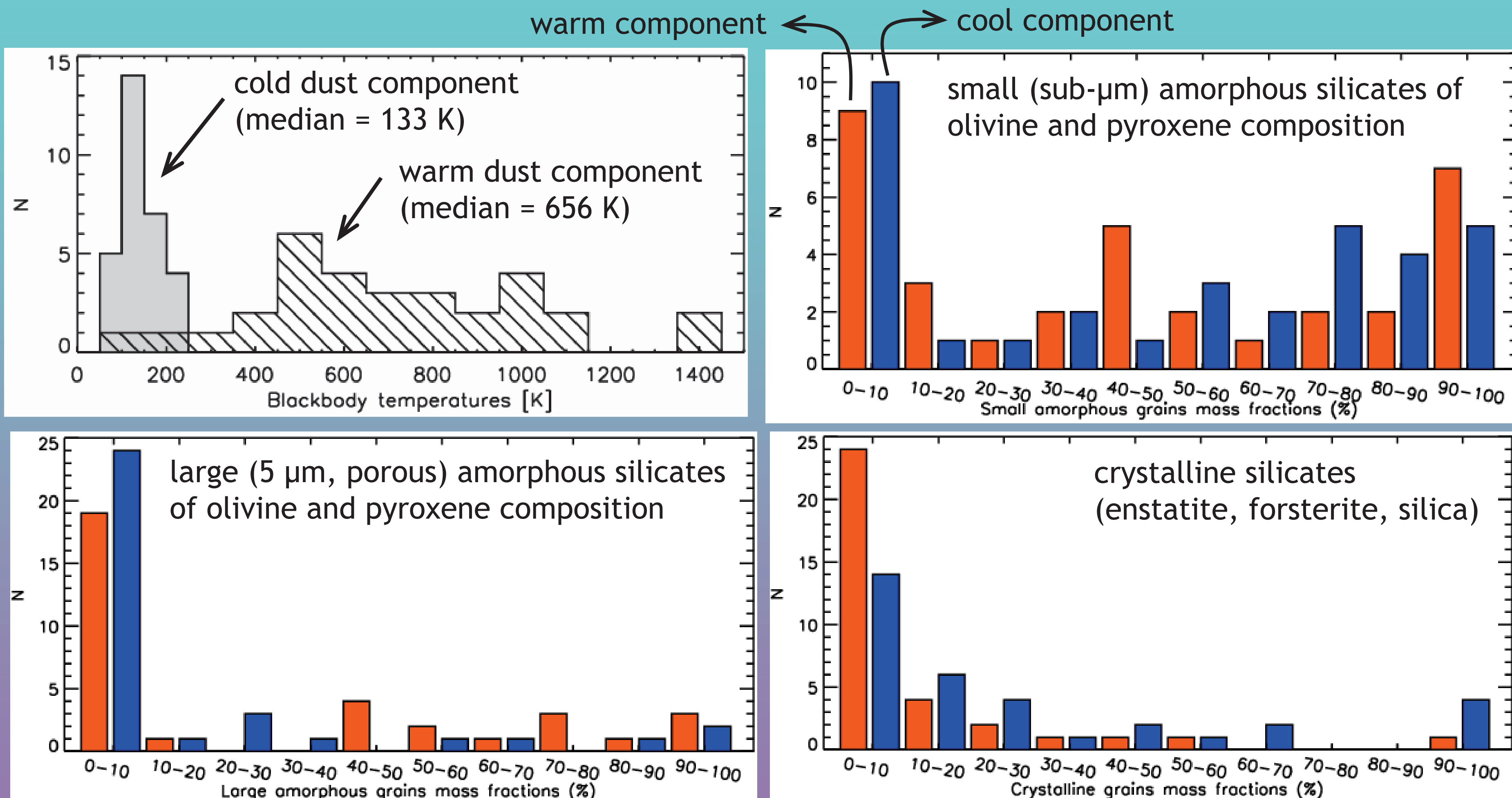
Spectral Types of CTTS and WTTS



CTTS and WTTS:
similar distribution of spectral types, but different median spectral types
→ WTTS have slightly later median spectral type

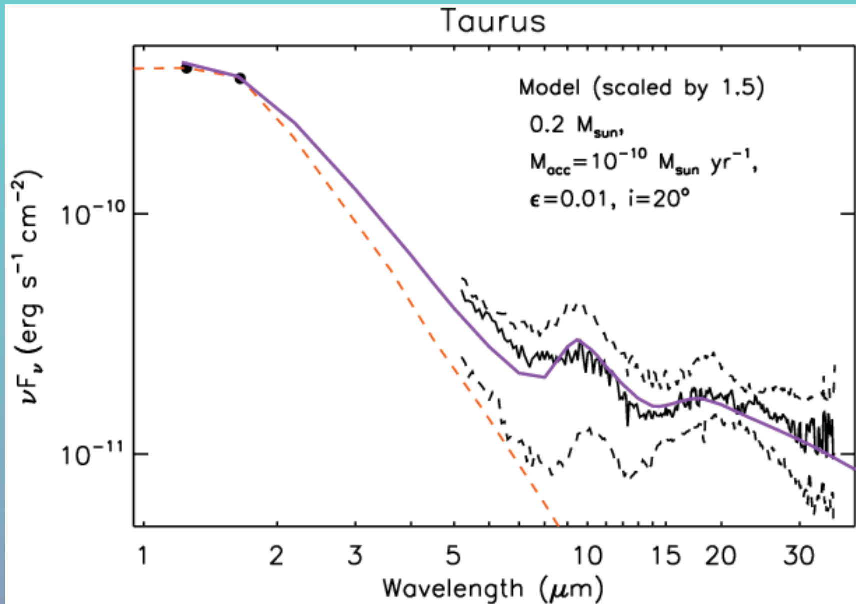
WTTS Dust Composition

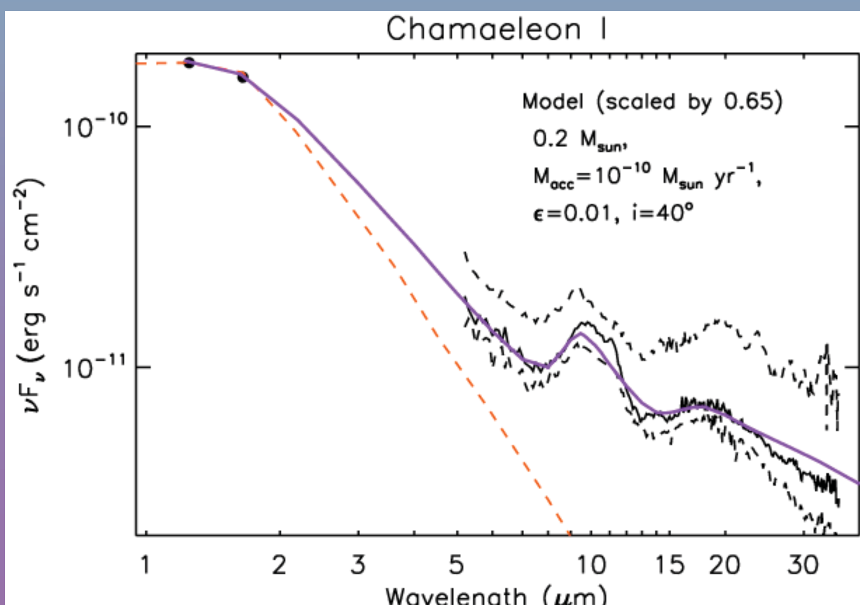
2-temperature dust model fits with 8 components for 34 WTTS (Tau, Cha I):



⇒ most WTTS: < 10% mass fractions of large and crystalline grains
→ mid-infrared emission is dominated by small grains and blackbody emission
(i.e., optically thick continuum or featureless emission from optically thin grains)

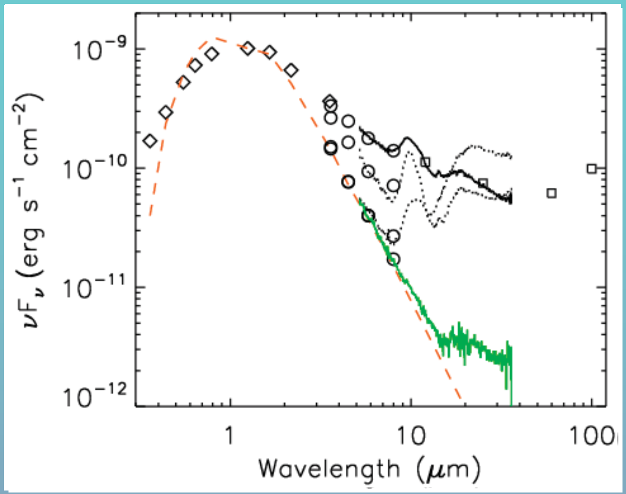
Models for the Median WTTS SED



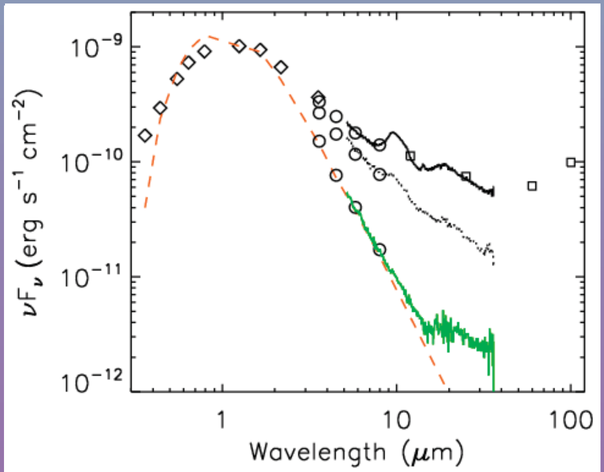


Median WTTS SEDs:
roughly described by disk models with low mass accretion rate (10^{-10} $M_\odot$ yr^{-1}) and with dust depletion in the upper disk layers by a factor of 100

Pathways of Disk Evolution and Dissipation

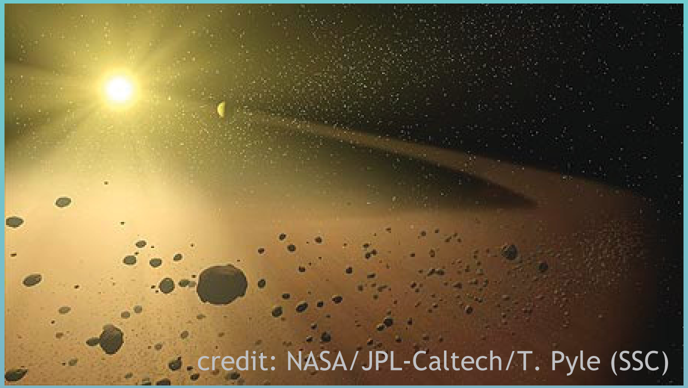


- formation of inner gaps, holes, then dissipation of the disk from the inside out?
  - gaps: indicative of planet formation
    → require planet to grow to a few tens of Earth masses in ~1 Myr → migrating protoplanet accumulates mass quickly
    → issues with gap formation, planet migration, dust in the inner regions; possibly cyclic event
  - inner (dust) holes: caused by dust growth, planets, photoevaporation, MRI-induced disk draining
    → different mechanisms likely operating in different disks and/or at different times (depending on disk mass, accretion rate,…)
    → issues with timescales and difficulty in determining main processes in a given disk



- steady depletion of material in the disk?
  → disk develops from flared to flat, optically thick, then to optically thin
  → main mechanism for late-type stars (with lower-mass disks)?

Conclusions



- Disk evolution in 1-3 Myr-old primordial disks: mid-infrared spectra reveal grain processing, grain growth, settling, and discontinuities (gaps, holes) in the inner disk (out to a few AU).
- Dust settling implies a depletion of small dust in upper disk layers by a factor of 100-1000.
- Transitional disks are likely formed by different mechanisms (photoevaporation; MRI-induced disk draining; planet formation), while disks with optically thin gaps suggest planet formation; they could be precursors of transitional disks.
- Disks around weak-lined T Tauri stars have lower excess emission at infrared wavelengths; they comprise transitional disks, optically thin disks, and settled, optically thick disks. They are probably at a more advanced evolutionary state than classical T Tauri stars.
- Disks likely undergo different evolutionary paths, some without the formation of an inner disk hole.
  - → Does the path depend on the stellar/disk mass?
  - → Dynamic disk evolution (turbulence, planet formation events)?